Machine protection measures for malfunctions of accelerator devices in J-PARC Main Ring
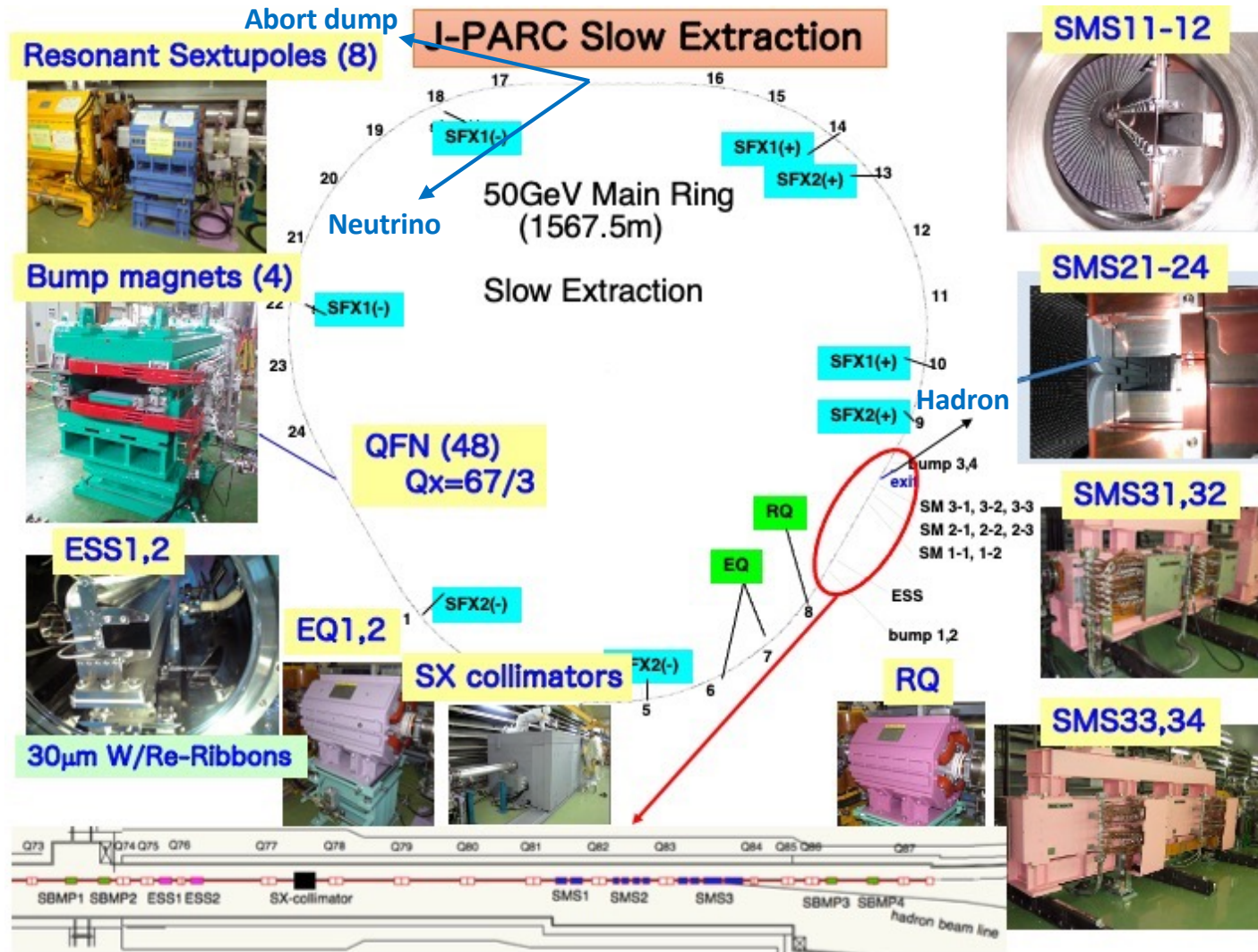
2024 Slow Extraction Workshop (MedAustron)
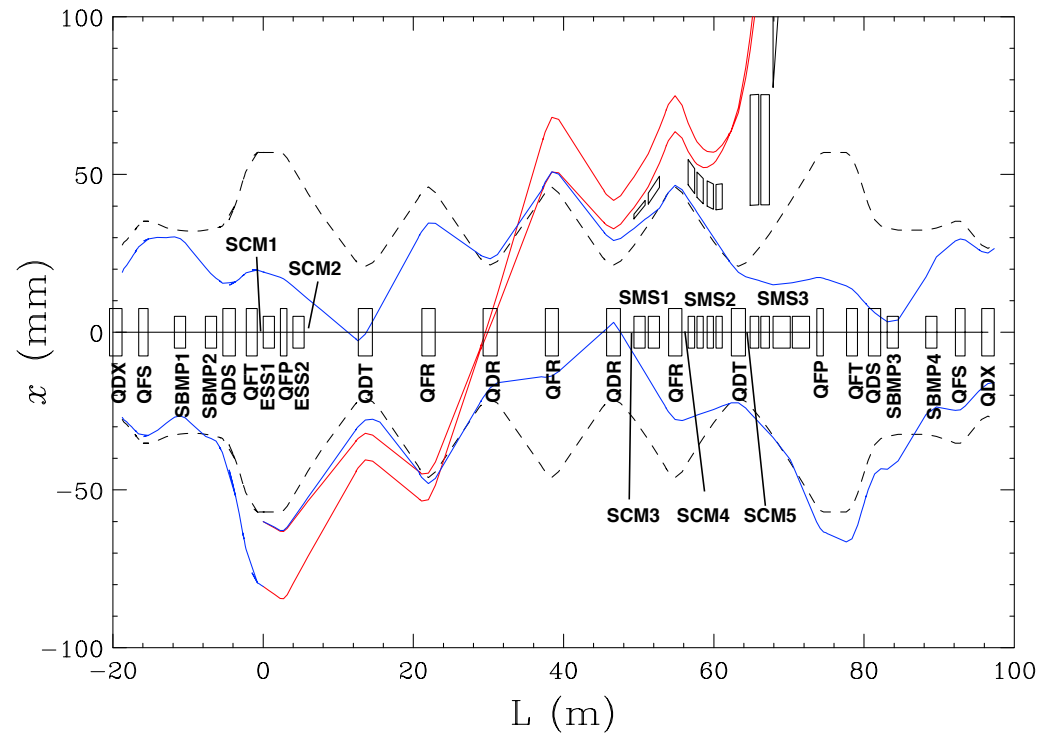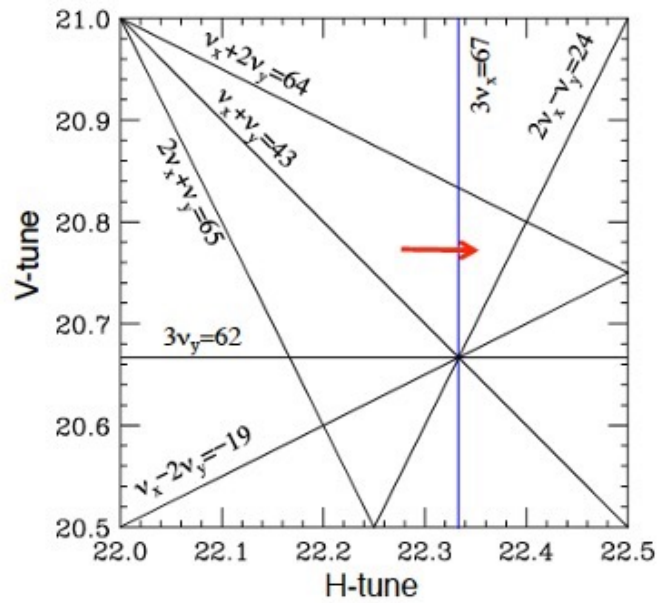
12 Feb. 2024

KEK/J-PARC   Masahito Tomizawa

1. J-PARC SX
2. Why do we not use a beam aborting by kickers for the SX operation
3. 2013 Hadron Hall incident and measures
4. SX Abort system
5. 2021 VCB trip and measures
6. Main BM and defocusing quadrupole trips and measures
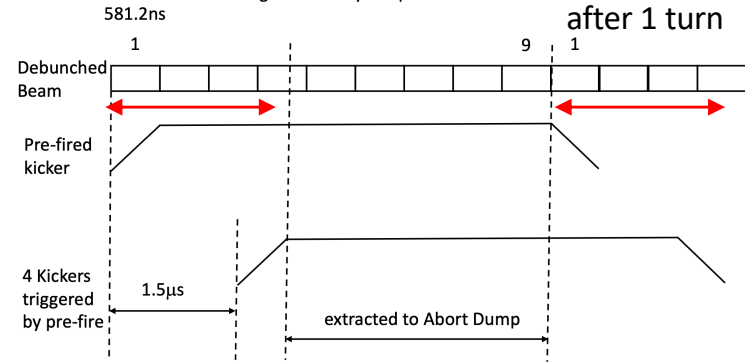7. summaries

J-PARC Slow Extraction

30GeV 7x10^13 protons extracted during 2sec. Every 5.2s (4.2s) cycle

Qx approaches from below to the 22.333 resonance

Anytime beam aborting by the horizontal 5 kickers is not applied for SX
Thyratron switches for the kickers could pre-fire during SX

A pre-fire of a thyratron has a risk to hit the circulating beam into the ESS blade since the bump orbit is produced around the ESS for the SX.
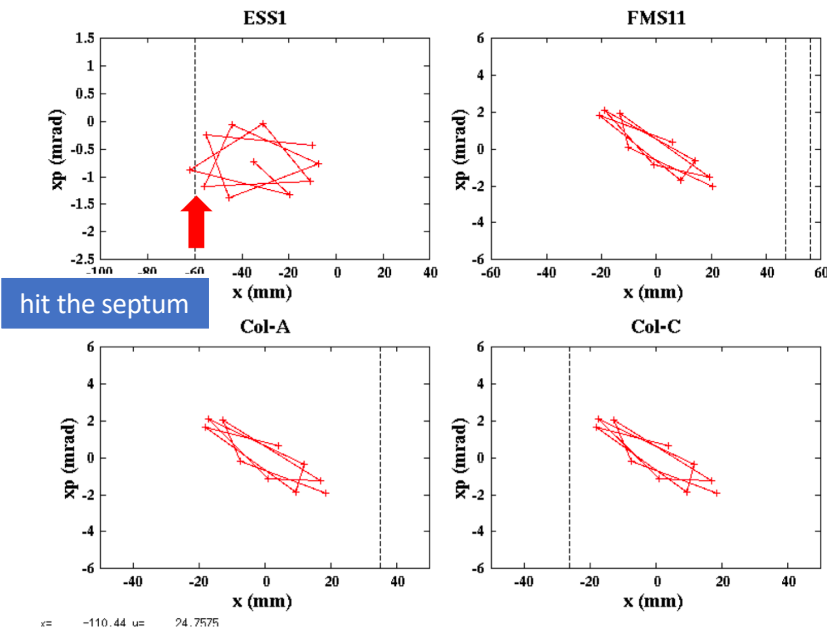-> An idea fires the remaining 4 kickers by the pre-fire.

after 1 turn

581.2ns

Debunched Beam

Pre-fired kicker

4 Kickers triggered by pre-fire

1.5μs

extracted to Abort Dump

The kicker rise time is slightly longer than the 581.2 ns bucket length

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beam center turn b turn motion

KM3 ON to abort (0 turn)
Current system

ESS1

FMS11

hit the septum

Col-A

Col-C

qx=22.3080;qy=20.7866

Bump: X=-35mm,xp=-0.73mrad

KM3 ON to abort (0 turn)
KM1,2,4,5 ON to abort (1 turn)

ESS1

FMS11

Bx=39.1m
±20.0mm@10pi

Bx=21.8m
±15mm@10pi

hit the electrode

Col-A

Col-C

Bx=17.3m
±13.1mm@10pi

Bx=10.1m
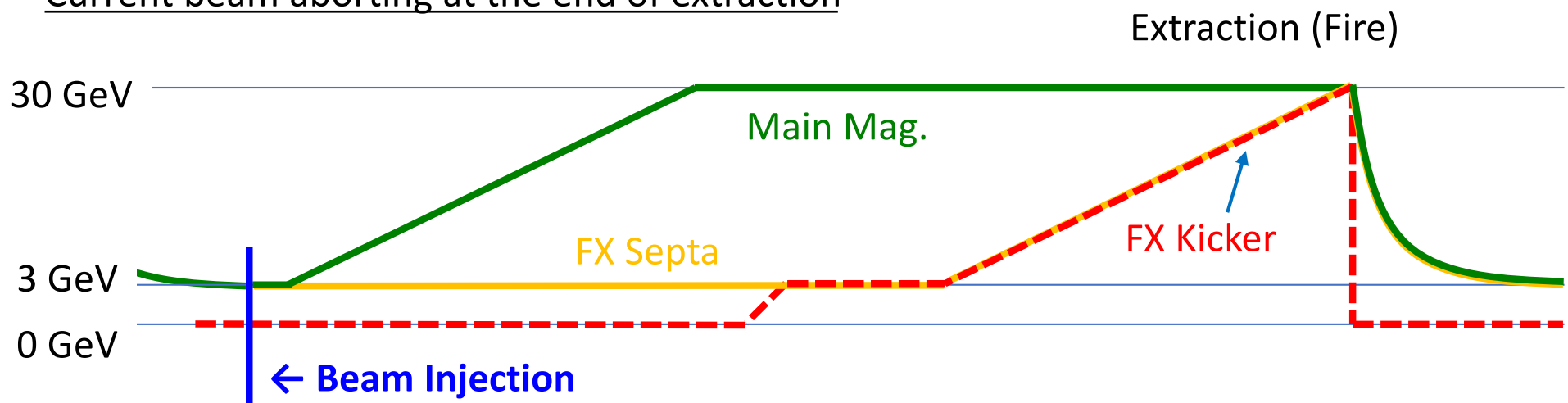±10.0mm@10pi
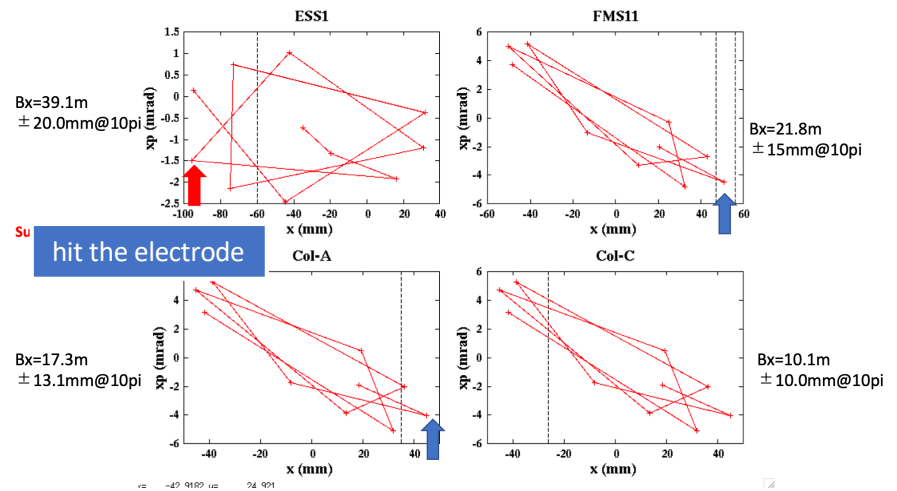
qx=22.3080;qy=20.7866

Bump: X=-35mm,xp=-0.73mrad

The Implemetation of this idea is now pending.

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4

Prefire rate increases with time duration kept at a high charging voltage of kickers

anytime beam aborting case

Extraction (Fire)

FX EDDY

30 GeV

Main Mag. & FX SM31 ~ 33

FX SM30

3 GeV

FX Kicker

0 GeV

← Beam Injection
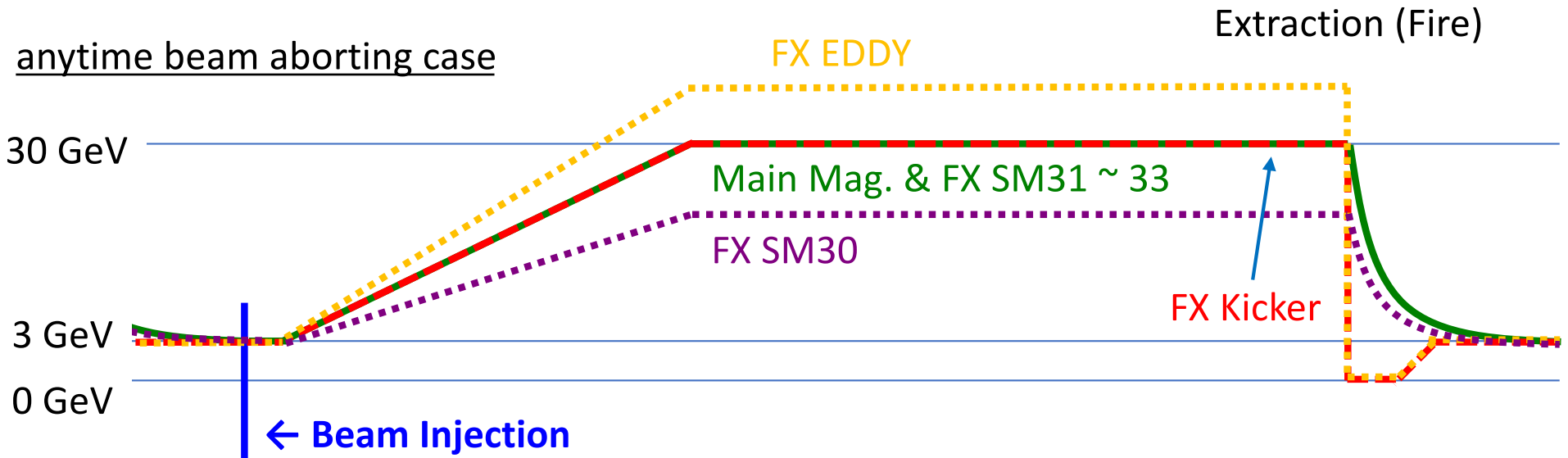
Pre-fire rate will increase by 150 times keeping the kicker voltage over 2.61 sec
will happen several times /per year.

Current beam aborting at the end of extraction

Extraction (Fire)

30 GeV

Main Mag.

FX Septa

FX Kicker

3 GeV

0 GeV

← Beam Injection

・A production gold target was evapolated by a short pulsed beam
・A radioactive material was diffused in the hall (insufficient vapor tightness of the target vessel)
  radiation exposure (0.1-1.7mSv)
 → 23months for the run recovery

2013 Accident   24kW beam

Proton beam

6.6 cm

gold target

Proton beam

2974℃   0   600 1200 1800 2400 3000 Temp. (℃)
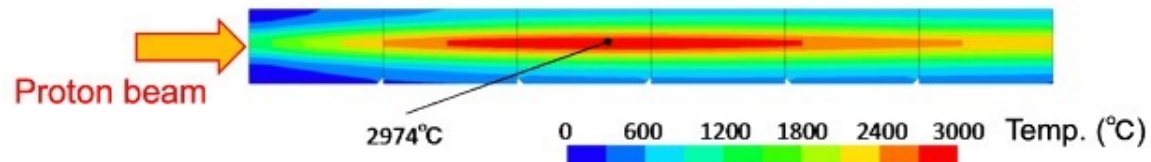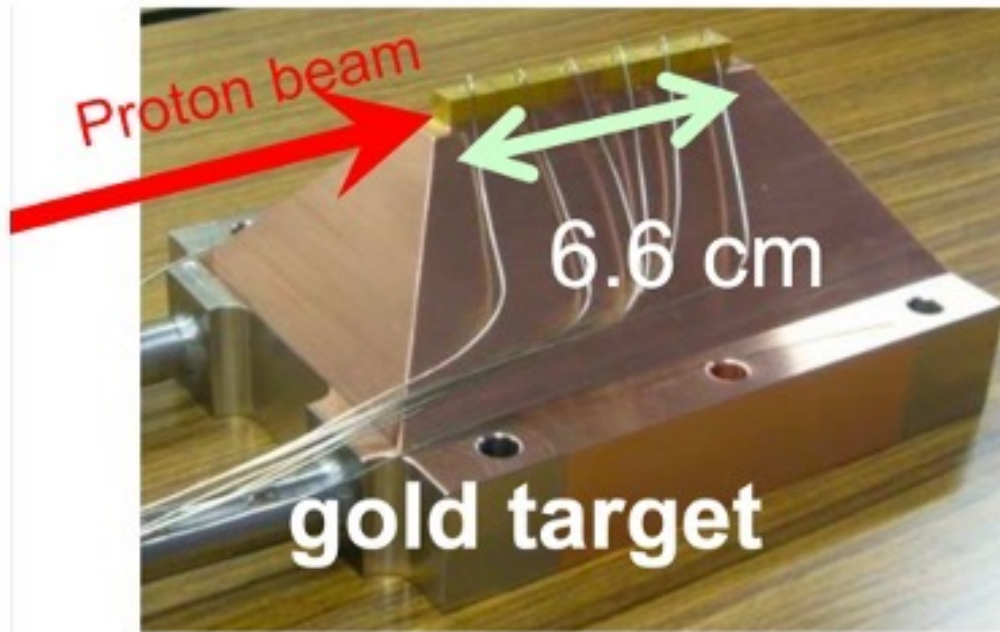
Calculated temperature profile immediately after the abnormal shot.
Gold (Au) melting point : 1064℃, boiling point : 2856℃   Au ⇨ liquid, gas

In 2013 Incident, Spill Feedback Quadrupole (EQ) Malfunctioned

EQ (focusing spill regulation quads) current increased in a pulse by malfunction
67% of the full beam (24kW 3x10^13 ppp) was estimated to be extracted
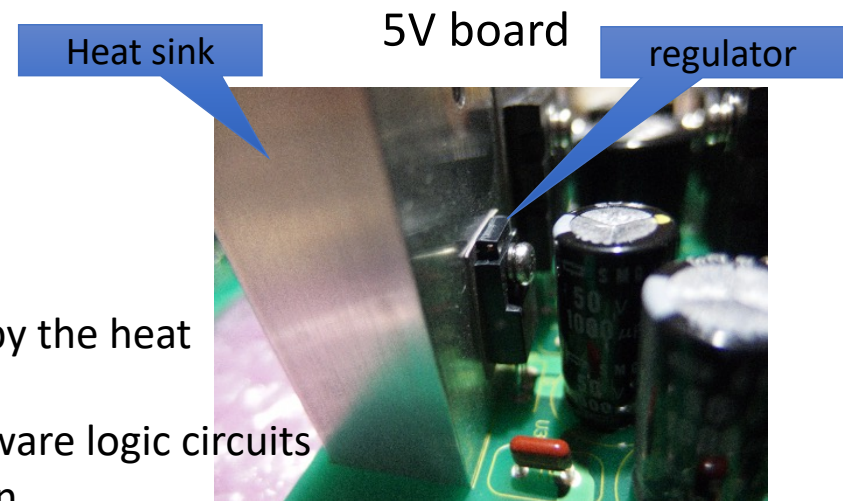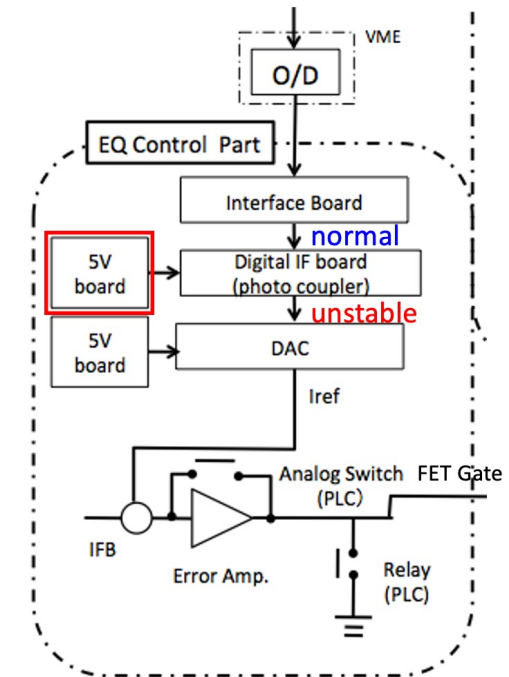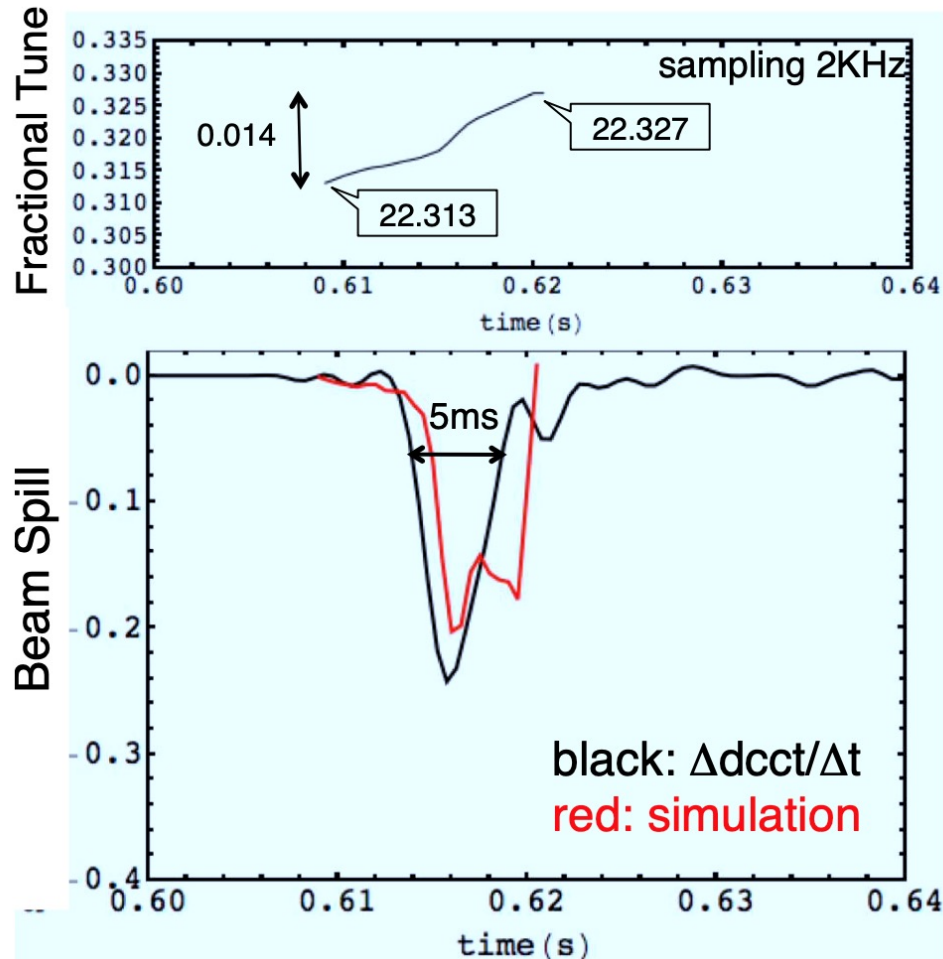
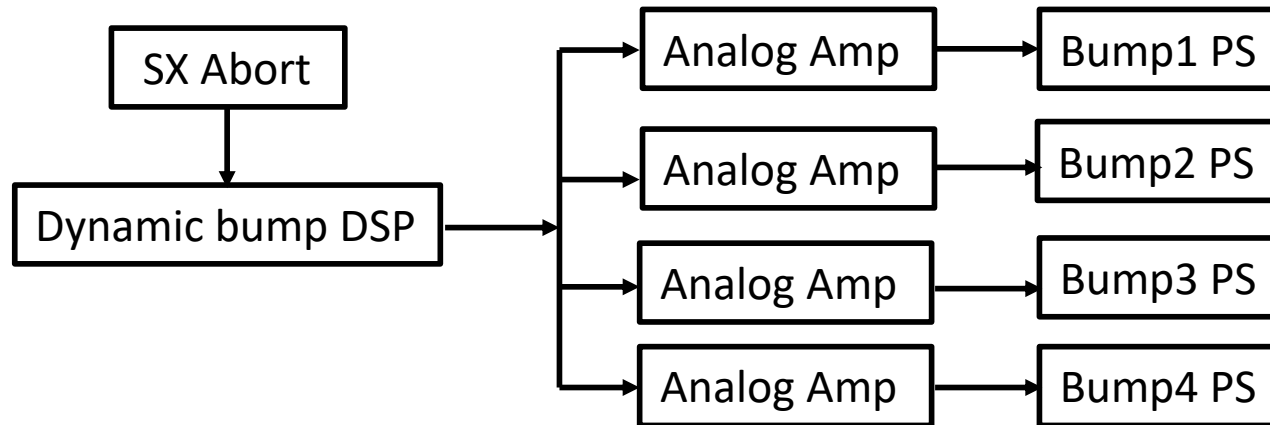A heat sink was missing, the voltage regulator was damaged by the heat
・Replaced to a new board with a heat sink
・ introduced a fast current stop board (<<1ms) using hardware logic circuits
  and analog switches for abnormal output current deviation

SX Abort System Flow   after 2013 incident
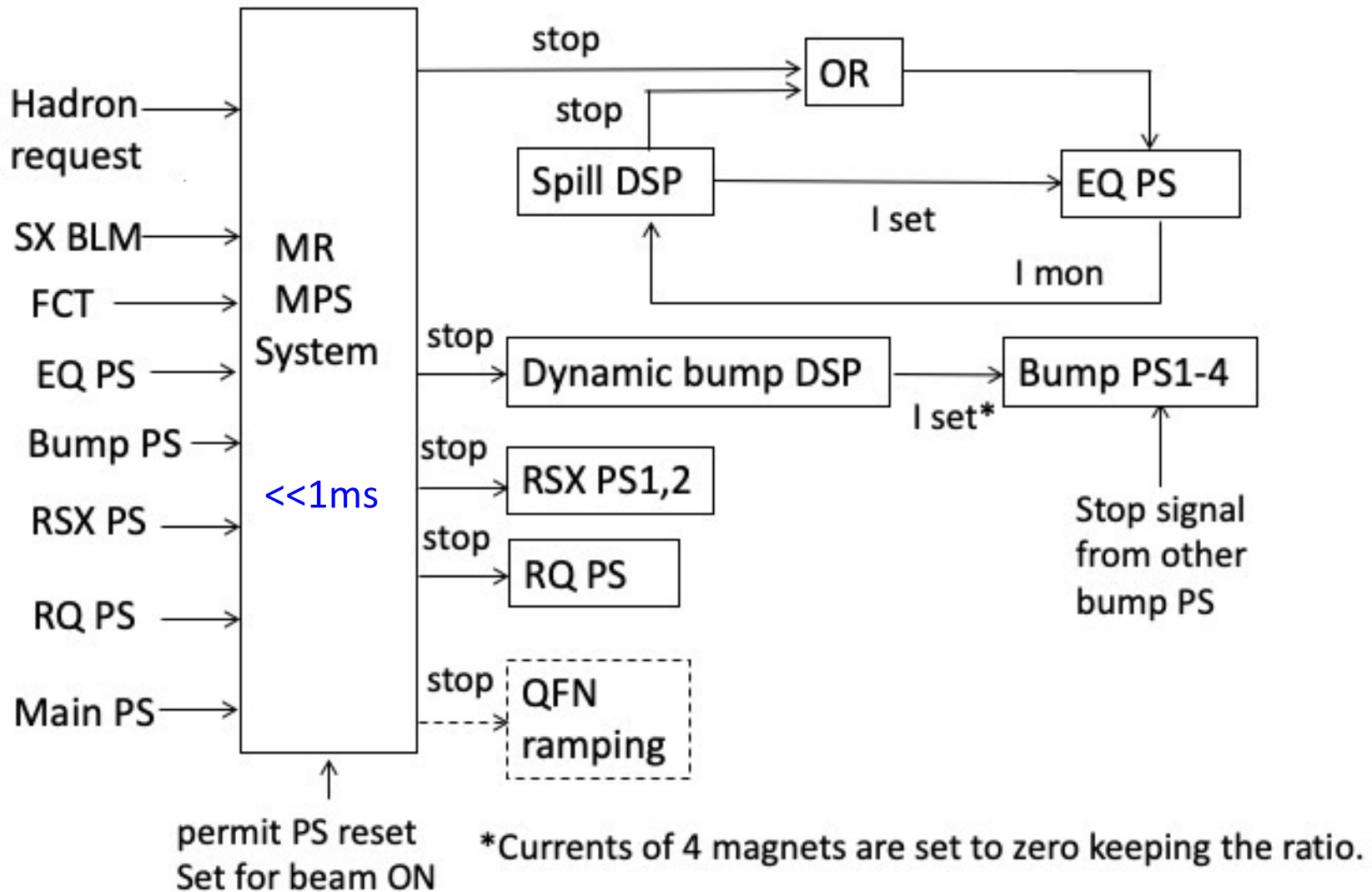
The SX abort system stops the slow extraction dumps the beam by kickers at the flat top end.

"SX Abort" for Bumps (before VCB Trip)

```
              ┌──────────────┐                      ┌──────────────┐      ┌──────────────┐
              │   SX Abort   │              ┌──────▶│  Analog Amp  │─────▶│  Bump1 PS    │
              └──────────────┘              │       └──────────────┘      └──────────────┘
                     │                      │       ┌──────────────┐      ┌──────────────┐
                     ▼                      ├──────▶│  Analog Amp  │─────▶│  Bump2 PS    │
        ┌────────────────────────┐          │       └──────────────┘      └──────────────┘
        │   Dynamic bump DSP     │──────────┤       ┌──────────────┐      ┌──────────────┐
        └────────────────────────┘          ├──────▶│  Analog Amp  │─────▶│  Bump3 PS    │
                                            │       └──────────────┘      └──────────────┘
                                            │       ┌──────────────┐      ┌──────────────┐
                                            └──────▶│  Analog Amp  │─────▶│  Bump4 PS    │
                                                    └──────────────┘      └──────────────┘
```

4 bump currents fall in 200 msec keeping current ratios to suppress an additional beam loss. The closed orbit condition is satisfied in any fall time.

9
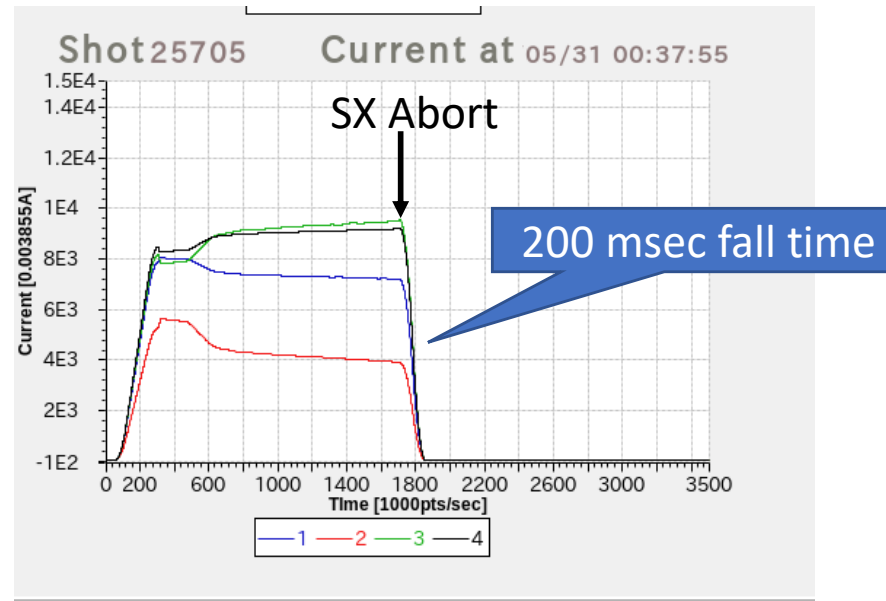
SX Abort Event

We can stop SX beam for the machine or beam loss trip to protect the devices (target,ESS,SMS,,,) within 1ms.
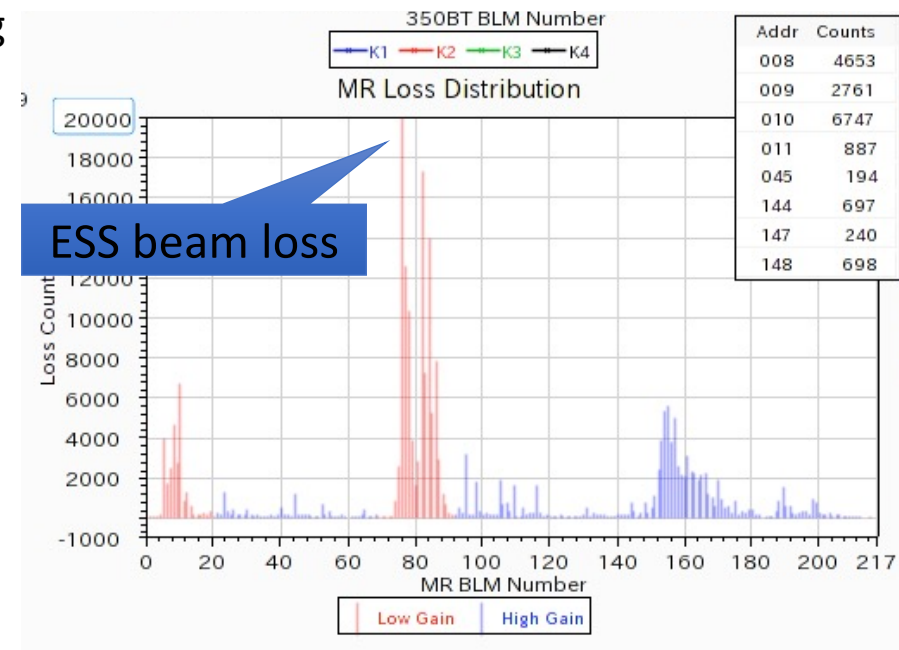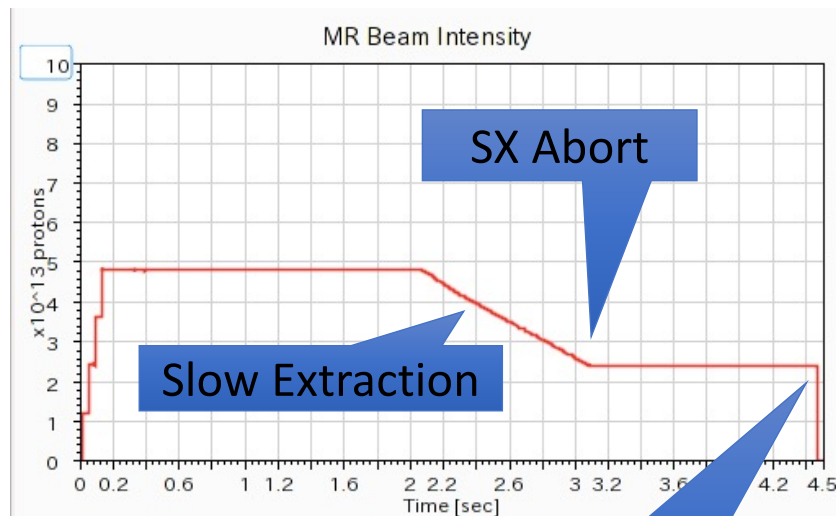The beam is dumped at the end of flat top.
This system is indispensable for present high intensity runs

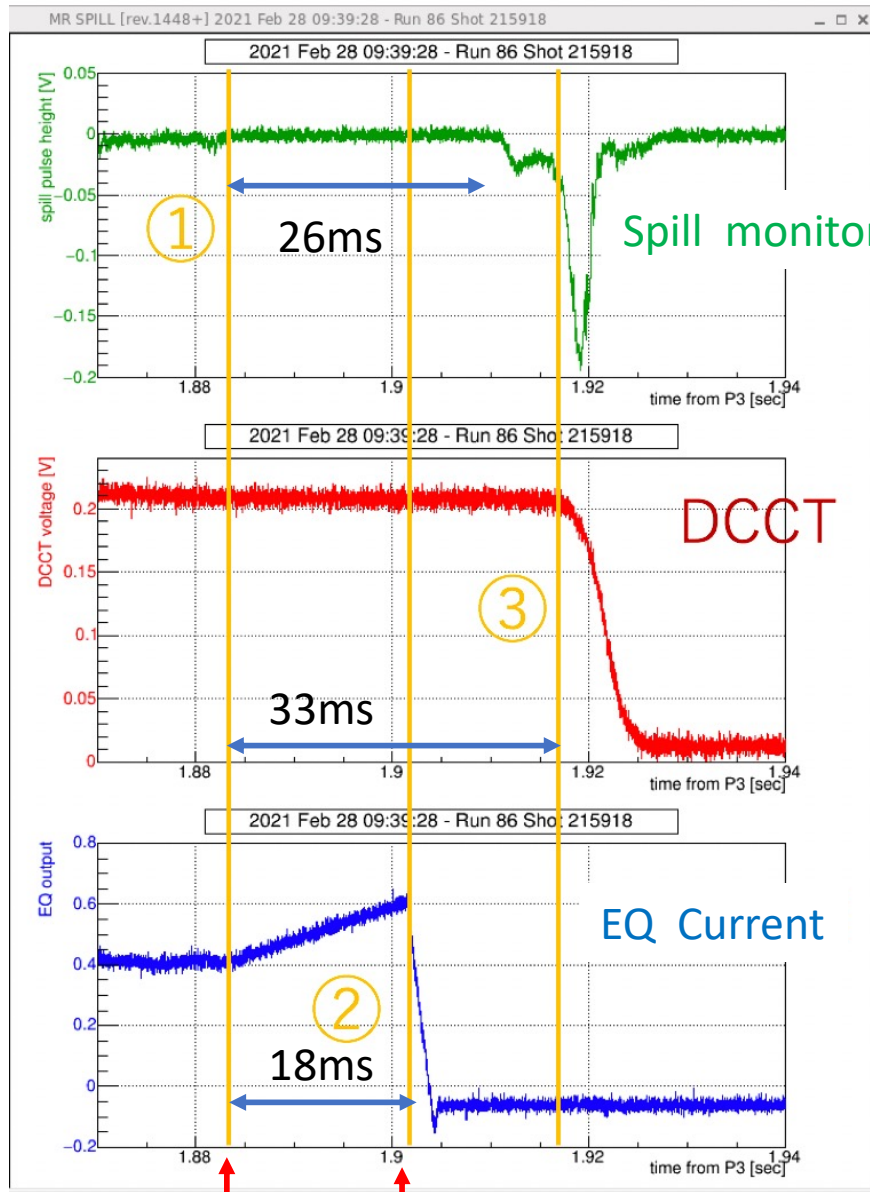SX Beam Study BLM76 (ESS1) beam loss count increase
2015/11/25 12:07 run65 #109878
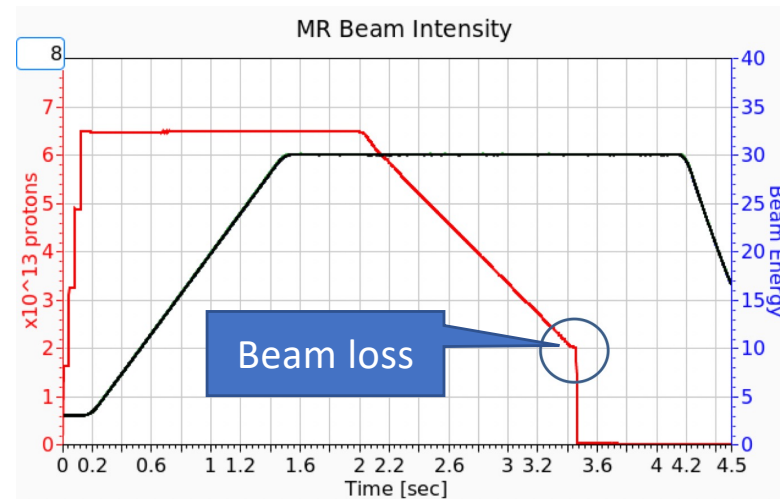
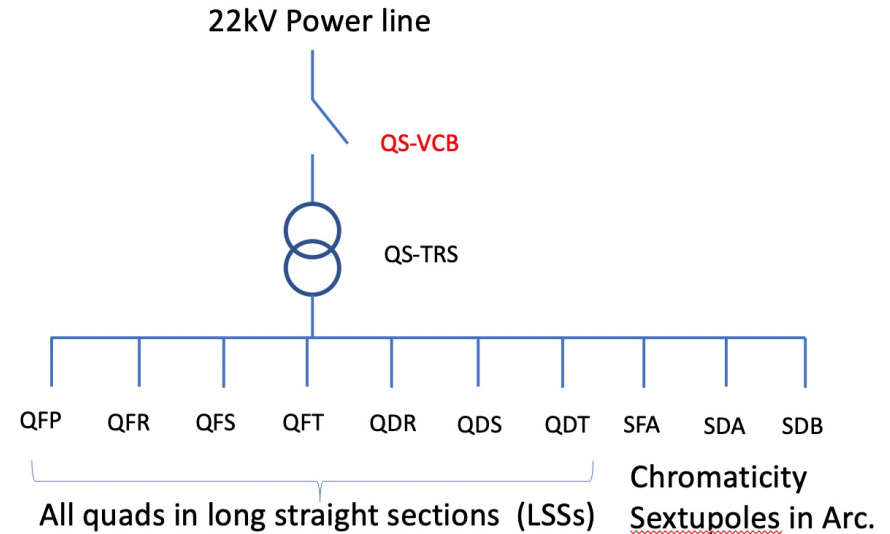Present MR can not abort beam at any timing

60kW (6.5x10^13 ppp, 5.2s cycle) SX run
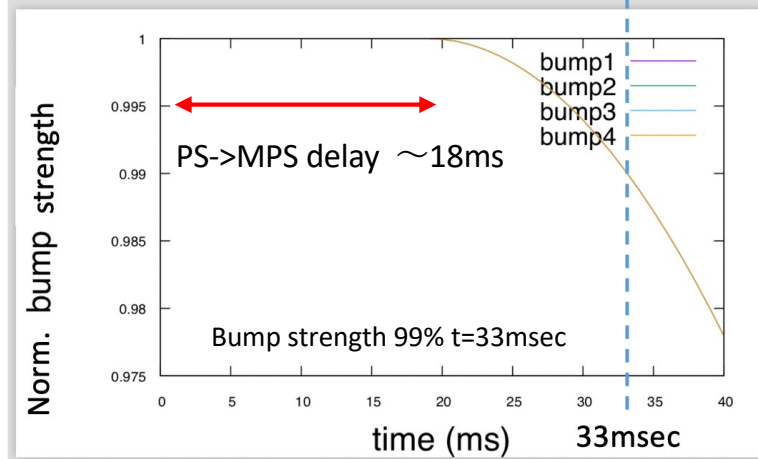
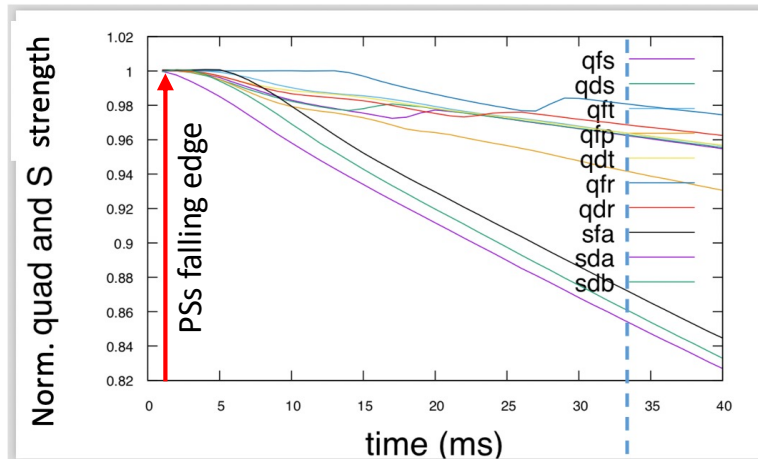VCB open/close sensor malfunction in 2021

VCB: Vacuum Circuit Breaker

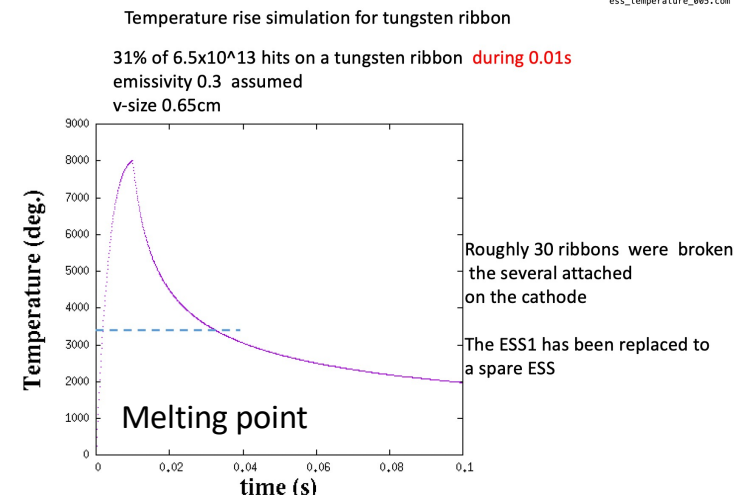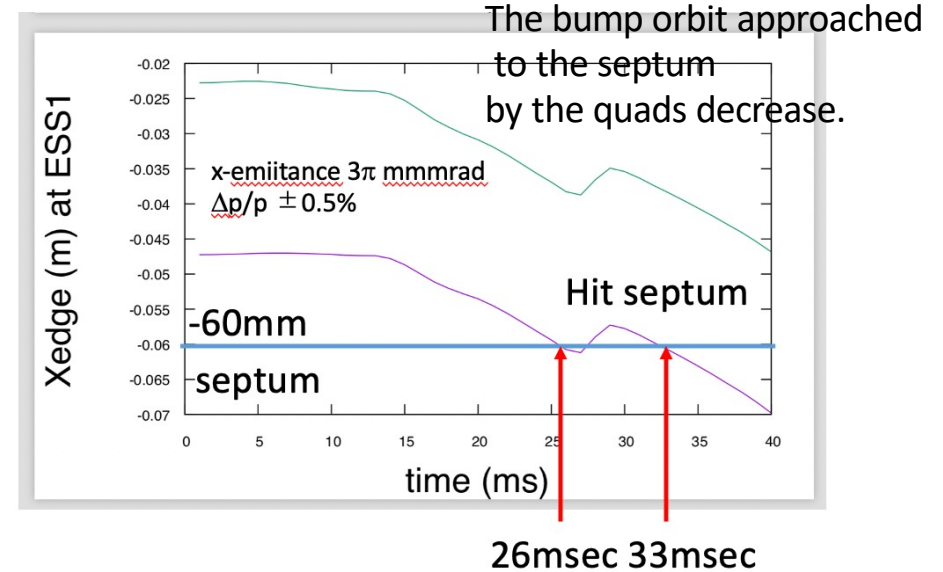quads fall start   SX Abort

Beam loss

Slow Extraction Bump Orbit and Ribbons Temperature Analysis in the VCB trouble

7 quads families in LSSs and chromaticity-sextupoles in ARCs were fallen down

Orbit and circulating beam edges calculation by the Quads fall pattern

The bump orbit approached to the septum by the quads decrease.

x-emiitance 3π mmmrad
$\Delta p/p \pm 0.5\%$

-60mm septum

Hit septum

26msec 33msec

PS->MPS delay ～18ms

Bump strength 99% t=33msec

33msec

Temperature rise simulation for tungsten ribbon

ess_temperature_005.com

31% of 6.5×10^{13} hits on a tungsten ribbon during 0.01s
emissivity 0.3 assumed
v-size 0.65cm

Roughly 30 ribbons were broken
 the several attached
on the cathode

The ESS1 has been replaced to
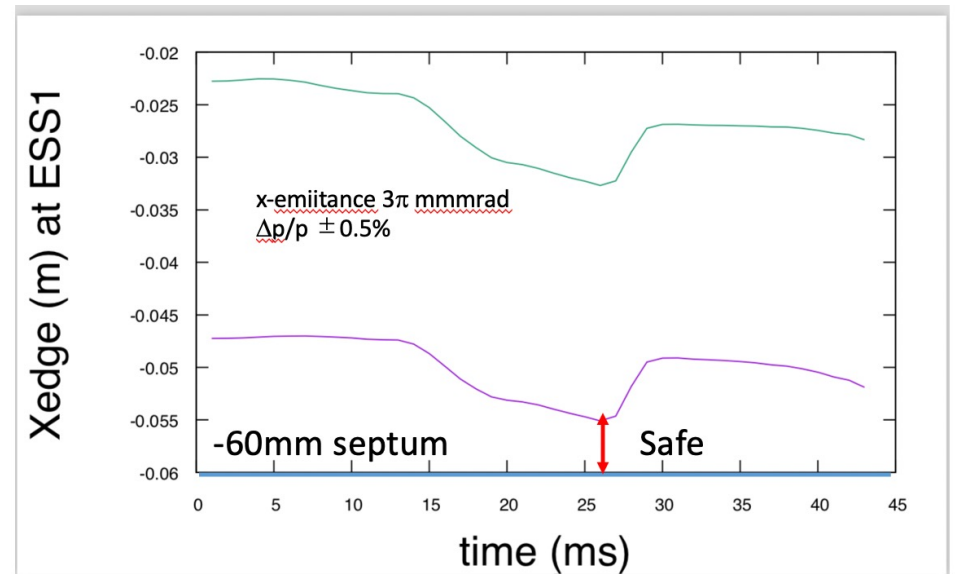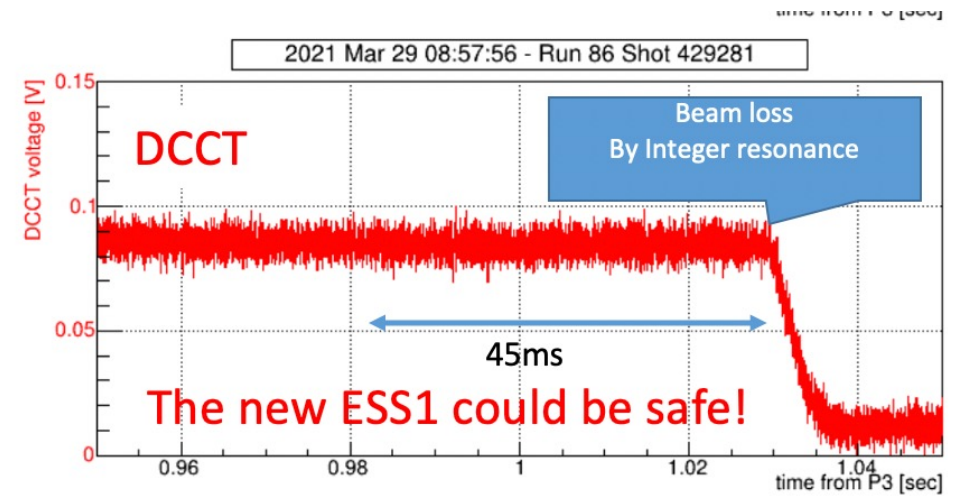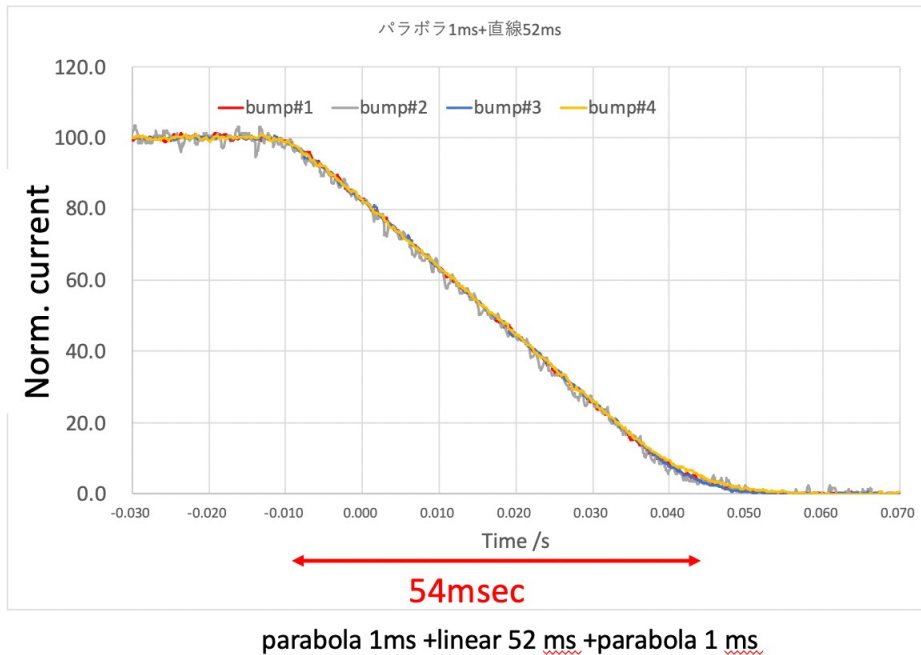a spare ESS

Melting point

Roughly 30 ribbons were broken, and some were attached to electrodes -> ESS was replaced with a spare
The ESS ribbons retraction structure has been improved for a newly built ESS spare.

VCB trip countermeasures for SX run recovery | The VCB trip happened again after replacing ESS1
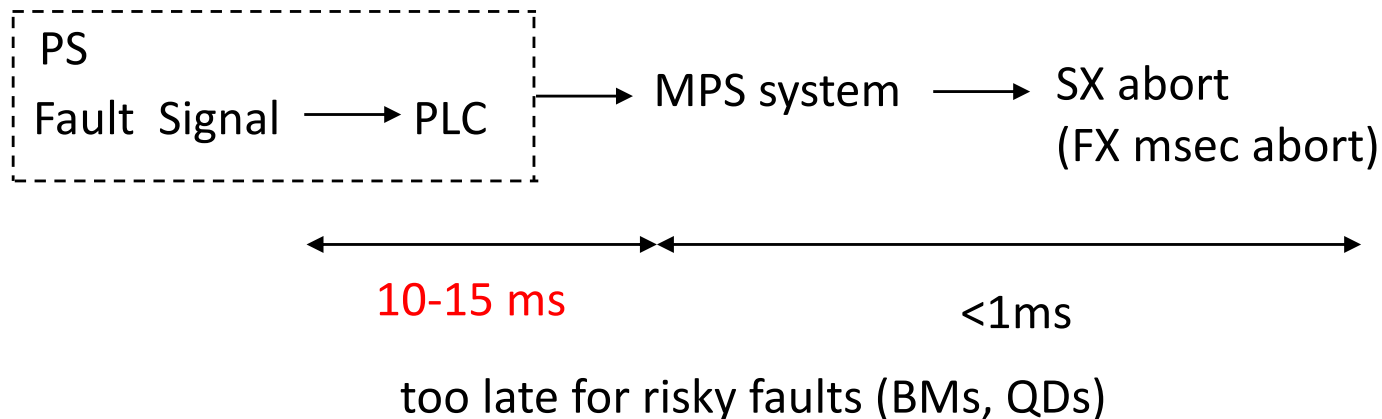
The Bump fall time by SX Abort is shorten
from **200 msec** to **54msec (near limit of the PSs)**

パラボラ1ms+直線52ms

54msec

parabola 1ms +linear 52 ms +parabola 1 ms

2021 Mar 29 08:57:56 - Run 86 Shot 429281

DCCT

Beam loss By Integer resonance

45ms

The new ESS1 could be safe!

x-emiitance 3π mmmrad
Δp/p ±0.5%

-60mm septum   Safe

The Bump fall-time shortening saved the new ESS from the second VCB trip!
A VCB trip signal has been directly fed into the MPS system after the 2nd trip.

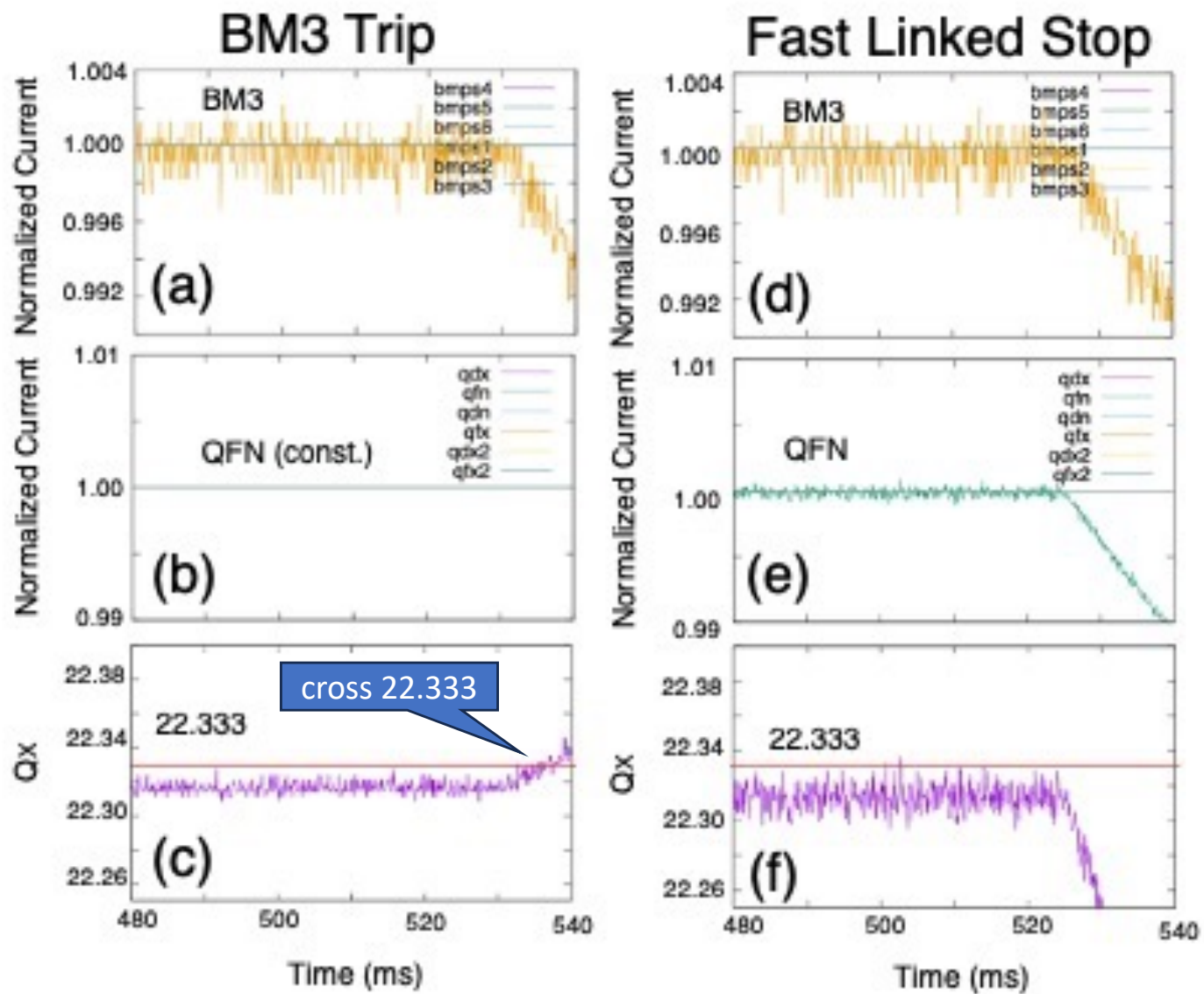Trip of Main power supply system for High repetition

New and reused main power Supplies for a high repetition

PS
Fault Signal $\longrightarrow$ PLC $\longrightarrow$ MPS system $\longrightarrow$ SX abort
(FX msec abort)

$\longleftrightarrow$ 10-15 ms $\longleftrightarrow$ <1ms

too late for risky faults (BMs, QDs)

The BM or defocusing quadrupole current-down by the trip
increases Qx and crosses the Qx=67/3 resonance,

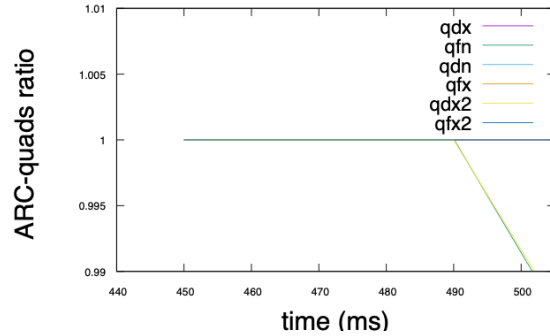which could deliver a short pulsed SX beam (〜msec.) to the production target

When the BMs or QDs faults happen,
quickly stop focusing QFN ("Fast Linked Stop")

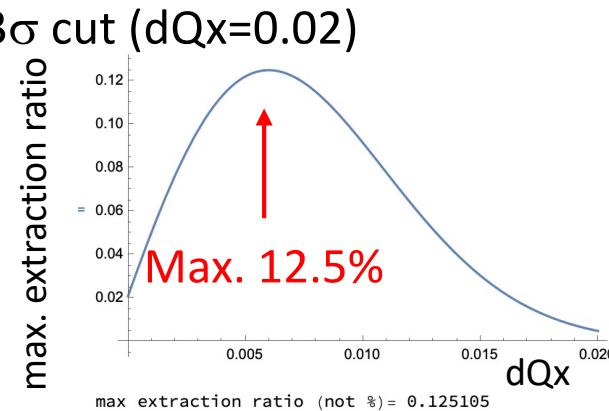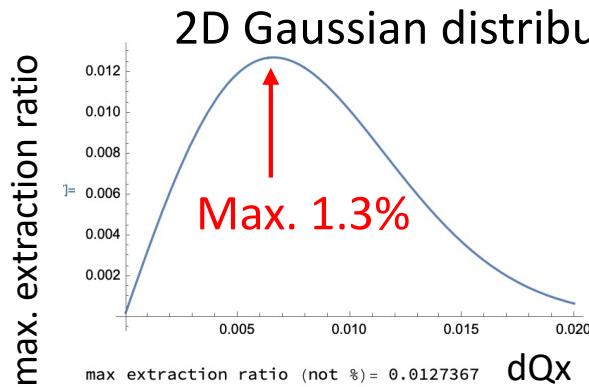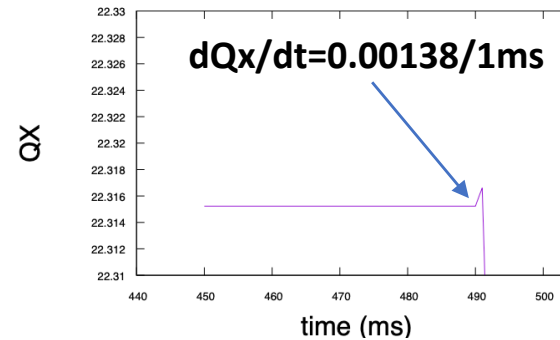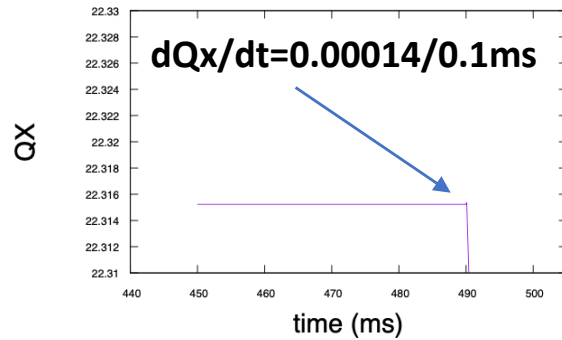14

BM3 Trip

Fast Linked Stop

15

◎Necessary response time from the trip to stop QFN

QDX2 trip

QFN stop delay 0.1ms

$dQx/dt=0.00014/0.1ms$

QFN stop delay 1ms

$dQx/dt=0.00138/1ms$

2D Gaussian distribution 3σ cut (dQx=0.02)

Max. 1.3%

max extraction ratio (not %)= 0.0127367

Max. 12.5%

max extraction ratio (not %)= 0.125105
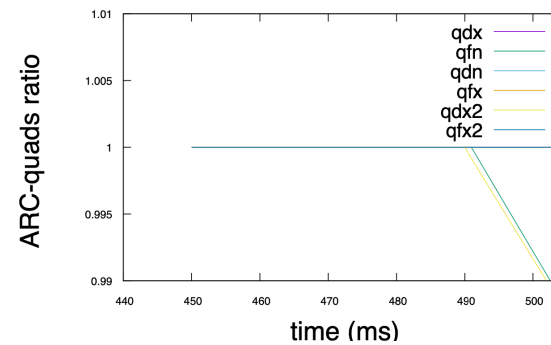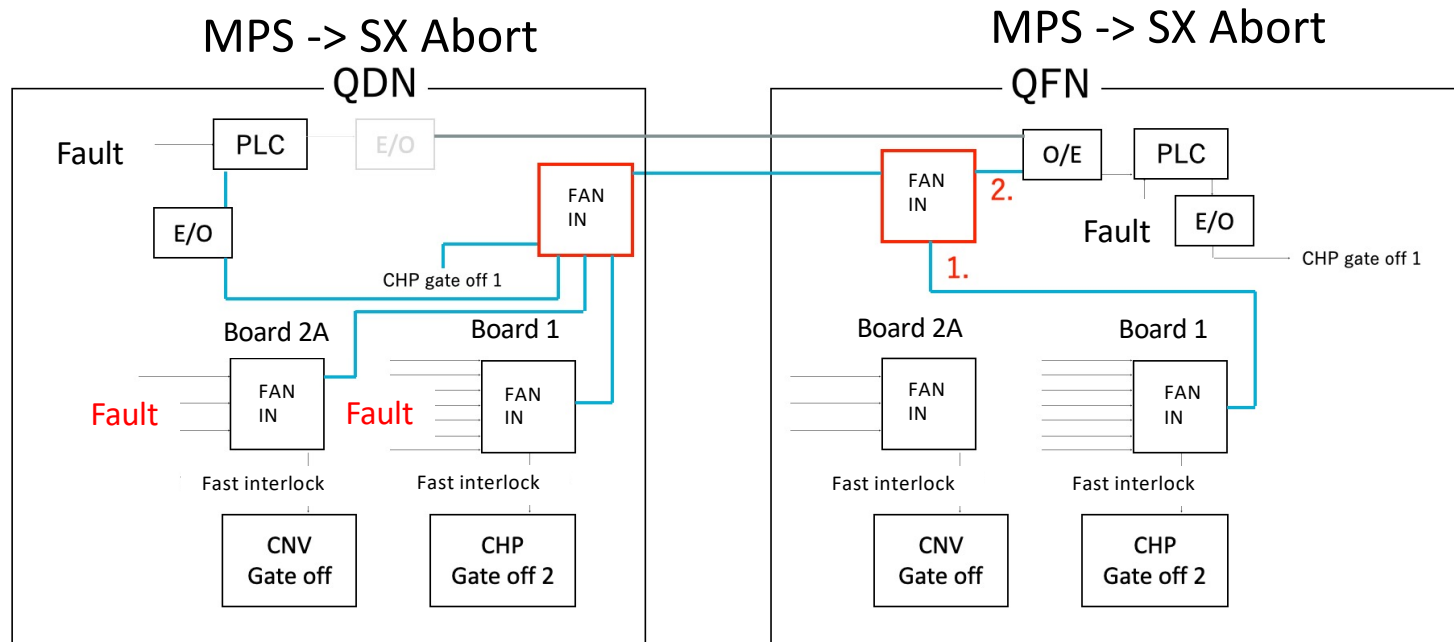
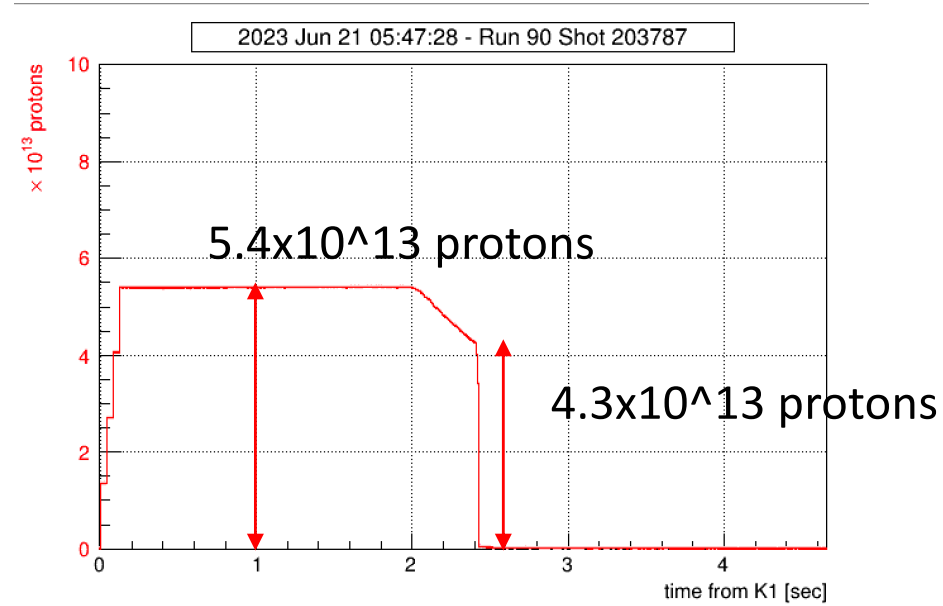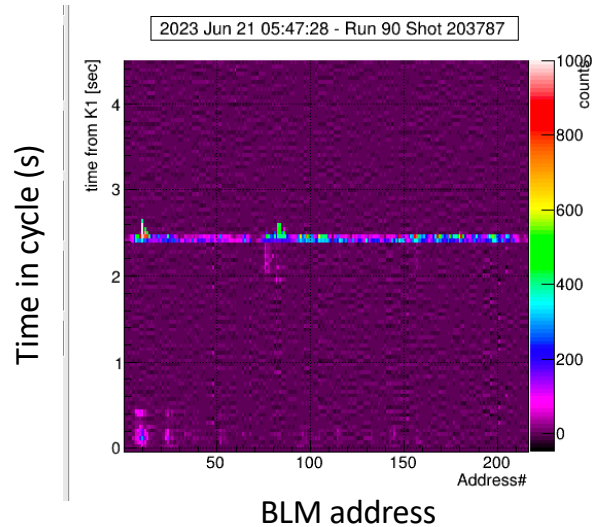We requested to improve the time response to 0.1ms level.

Main power supply system for High repetition

・ New Nichicon QDN, QDT, QDR and 1-6 BM PSs

・ Reused Toshiba QDX1,QDX2,QDS1,QDS2 PSs

interlocks have been modified to stop QFN within 0.1ms
before the 2023 SX-30GeV user operation

A BM2 trip happened during 30GeV SX in 2023!

2023 Jun 21 05:47:28 - Run 90 Shot 203787

time from K1 [sec]

Time in cycle (s)

BLM address

Address#

2023 Jun 21 05:47:28 - Run 90 Shot 203787

$\times 10^{13}$ protons

5.4x10^13 protons

4.3x10^13 protons

time from K1 [sec]

- BM2 fault happened at 0.4s after SX start
- beam loss in the whole MR
- BM2 fault -> SX Abort
  BM2 fault -> QFN fast linked stop

Rate monitor at the target

Count (/1ms)

Timing
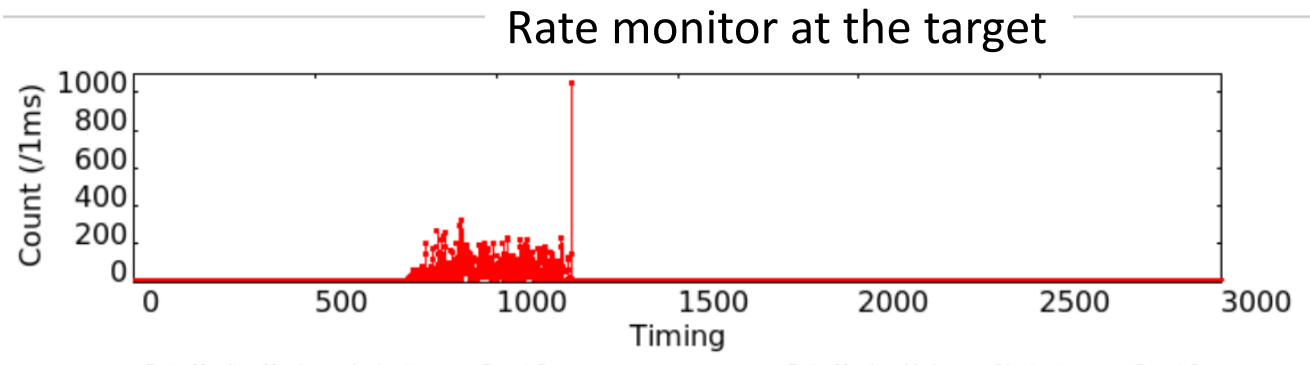
A very small beam extracted and delivered to the target
No temperature rise observed
The QFN fast-linked stop worked well and saved the target!

Summaries

- The EQ malfunction delivered a short pulsed beam and broke the target.
    -> The malfunction source was identified and replaced

- SX Abort System

- The VCB malfunction for the straight section quadrupole distorted the bump orbit.
   The circulating beam hit the septum ribbon.
    -> proportionally fallen in a shorter time (54ms <-200ms)

- Bending PS, defocusing quadrupole PS Trips
   can deliver a short-pulsed beam to the target
    -> Fast-linked QFN stop

- In the bump orbit check in the bunched beam mode in 2017,
    H-chromaticity was slightly >0   (below transition) by chance,
    a coherent beam oscillation was excited
   and the circulating beam broke the ESS ribbons

- SX bump PS Trip
   can distort the bump orbit, which could approach the ESS ribbons.
   When one bump PS stops,
   the other bump PSs can be stopped by a fast-linked bump stop system (300μs).
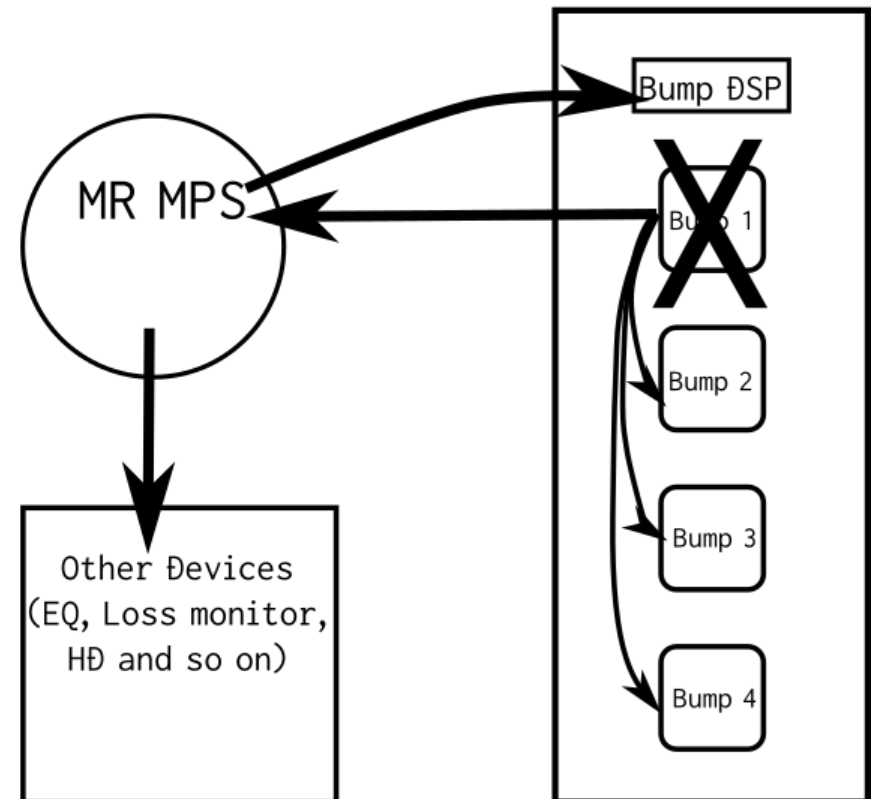
Other Trips

SX Abort action
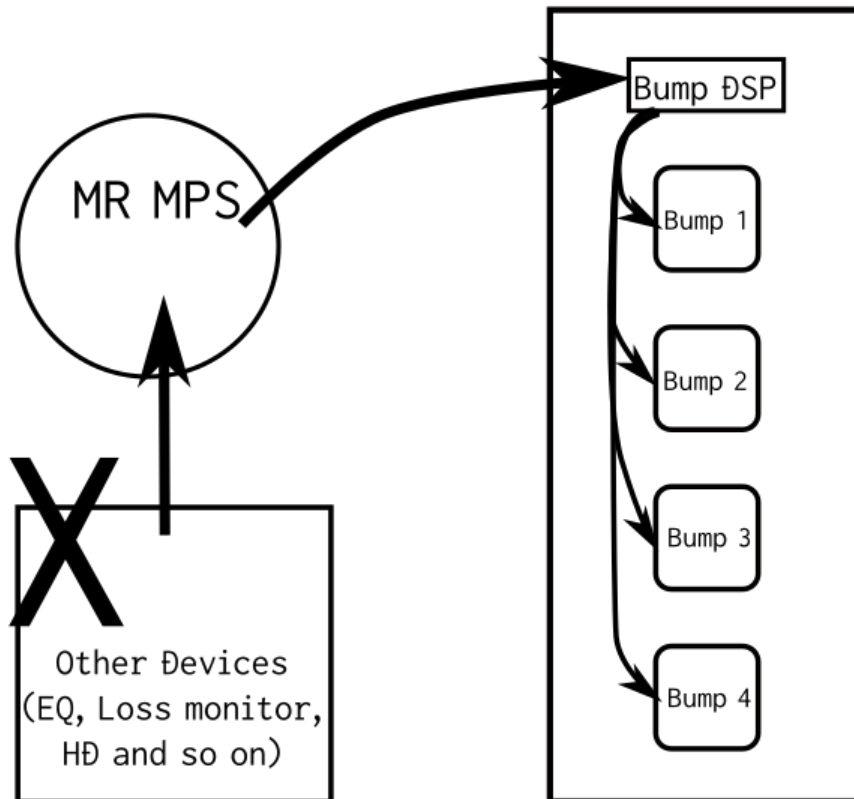
Bump P.S. Trip
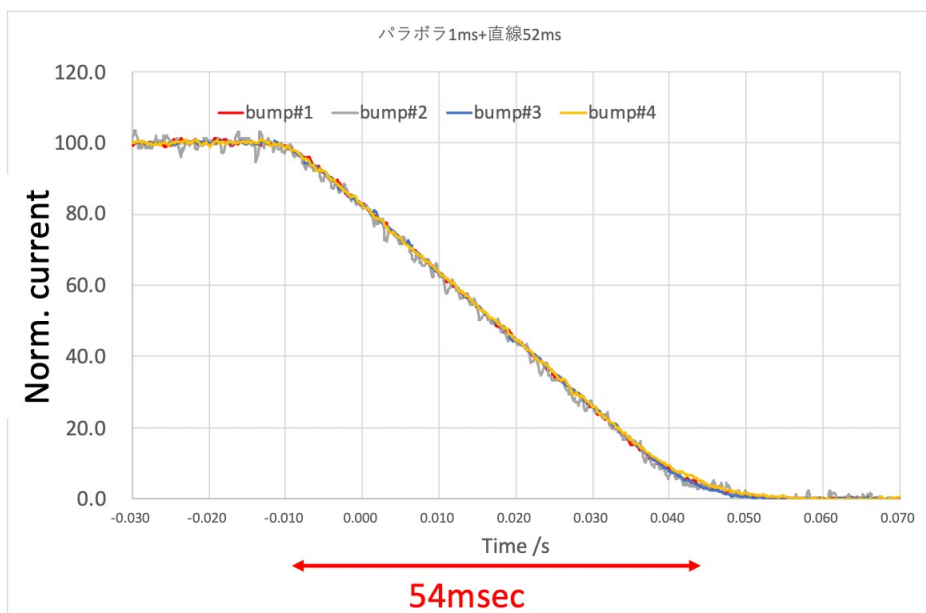
Fast-self-linked bump stop action

E. Yanaoka

PLC based: max delay 8ms
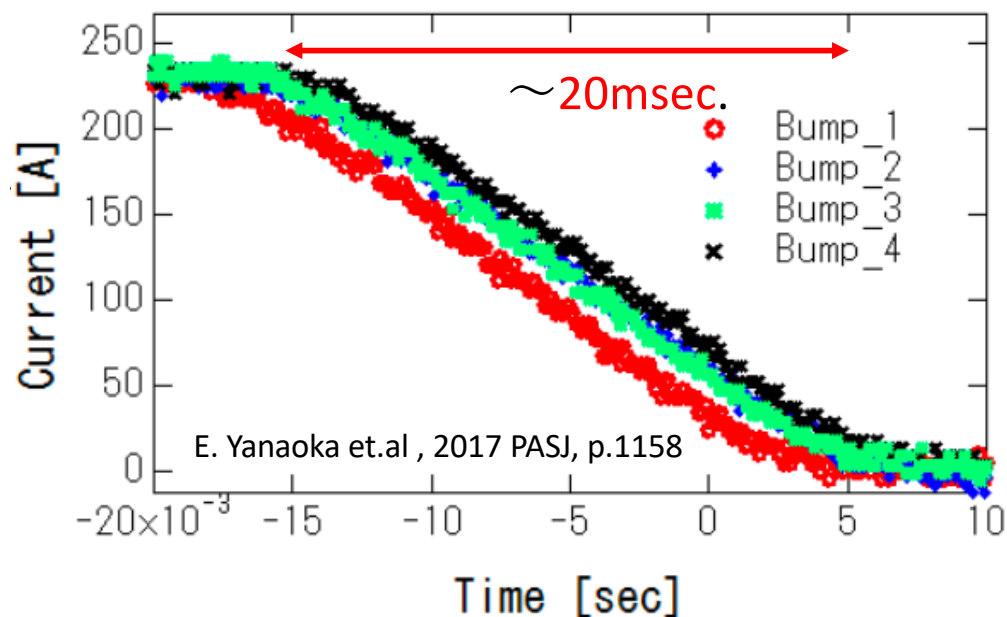-> FPGA based: delay 0.3ms (2022->)

SX Abort action

Bump Current Fall Pattern
(proportionally fallen by bump DSP)

parabola 1ms +linear 52 ms +parabola 1 ms

Fast-self-linked bump stop action

Fast Bump Current Fall Pattern
(not proportional)

E. Yanaoka et.al , 2017 PASJ, p.1158

Bump1 Stop delay 2.8ms (before FPGA based)