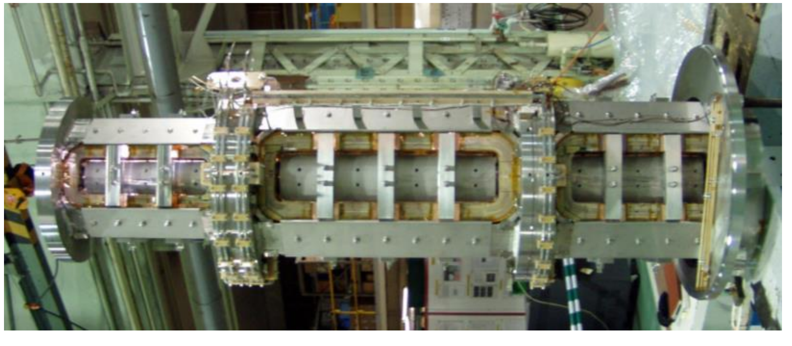
Radiation Effects in Superconducting Quadrupoles for BigRIPS In-flight Separator at RIKEN

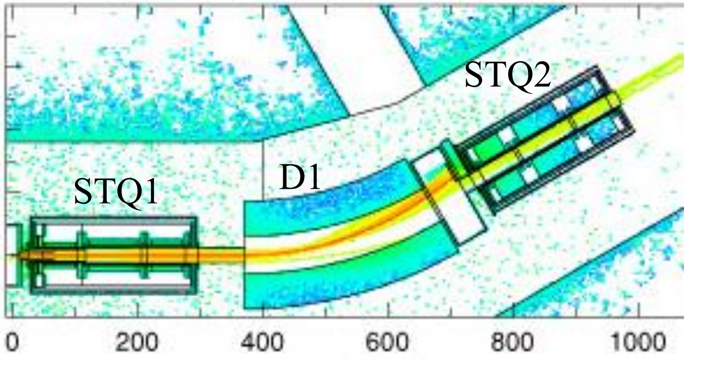
K. Kusaka, M. Ohtake, K. Yoshida, K. Tanaka, H. Mukai, Y. Uwamino, and T. Kubo

Contents

- Introduction (Facility, Magnet)
- Beam(Radiation) Heat load
- Dose Estimate ~1MGy in 9 years
- Impurities in He gas (T, CH_4)
- Excitation voltage & coil movement

"Any indication of degradation of superconducting coil ?"



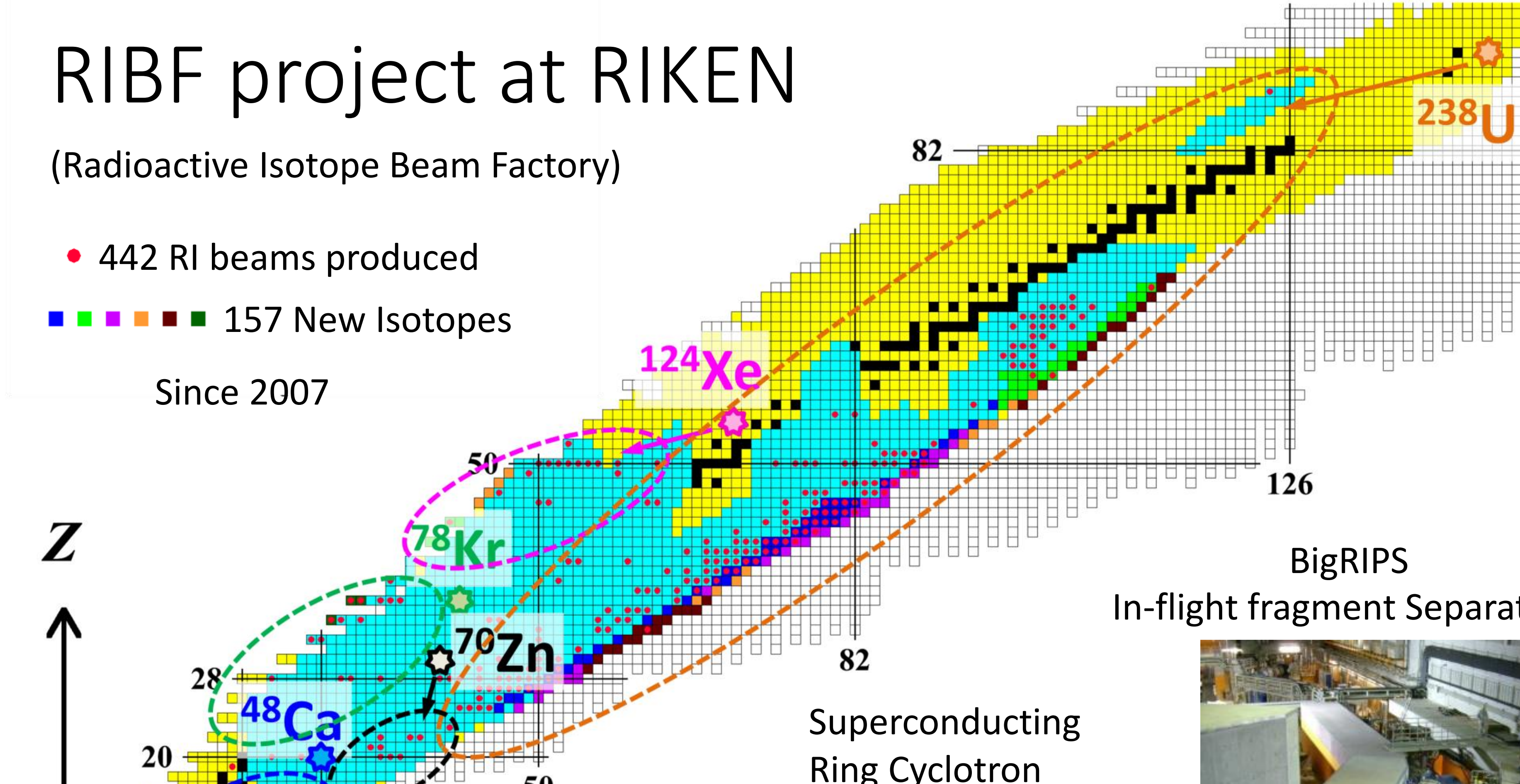


RIBF project at RIKEN

(Radioactive Isotope Beam Factory)

- 442 RI beams produced
- 157 New Isotopes

Since 2007

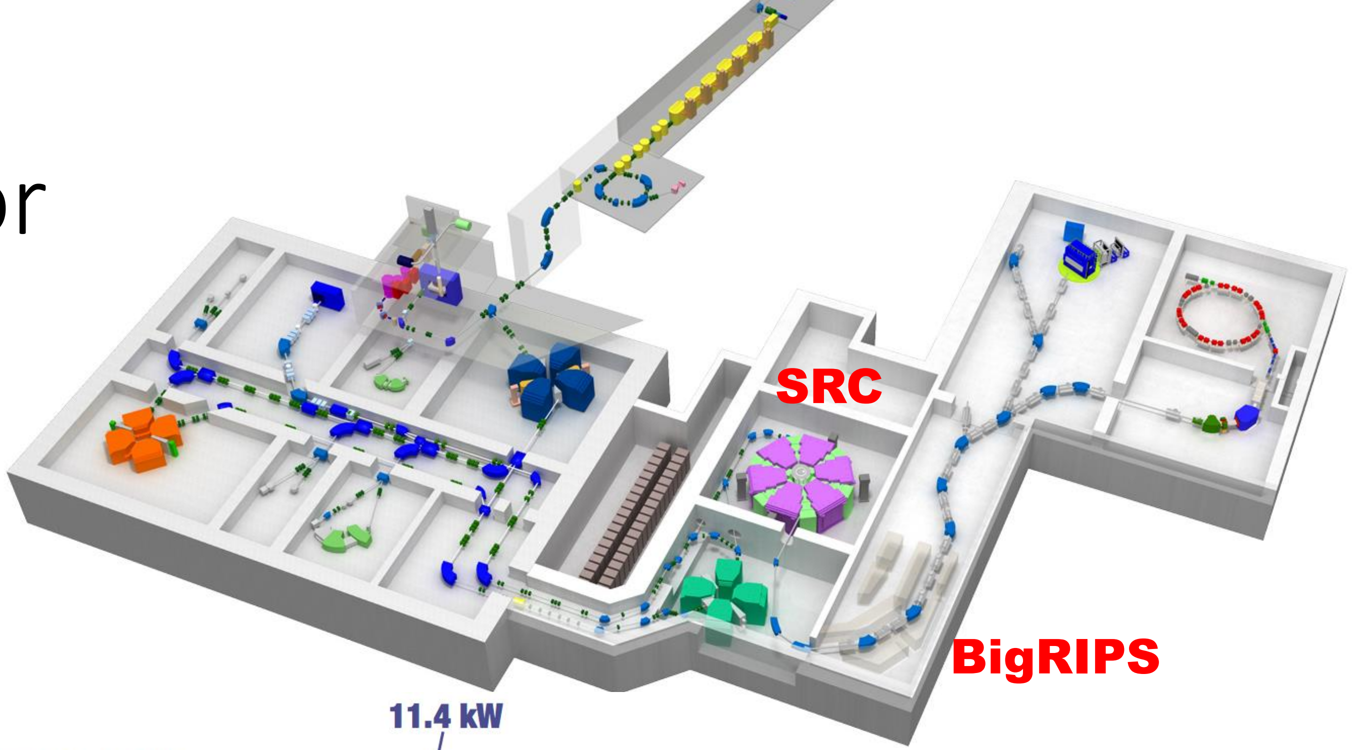


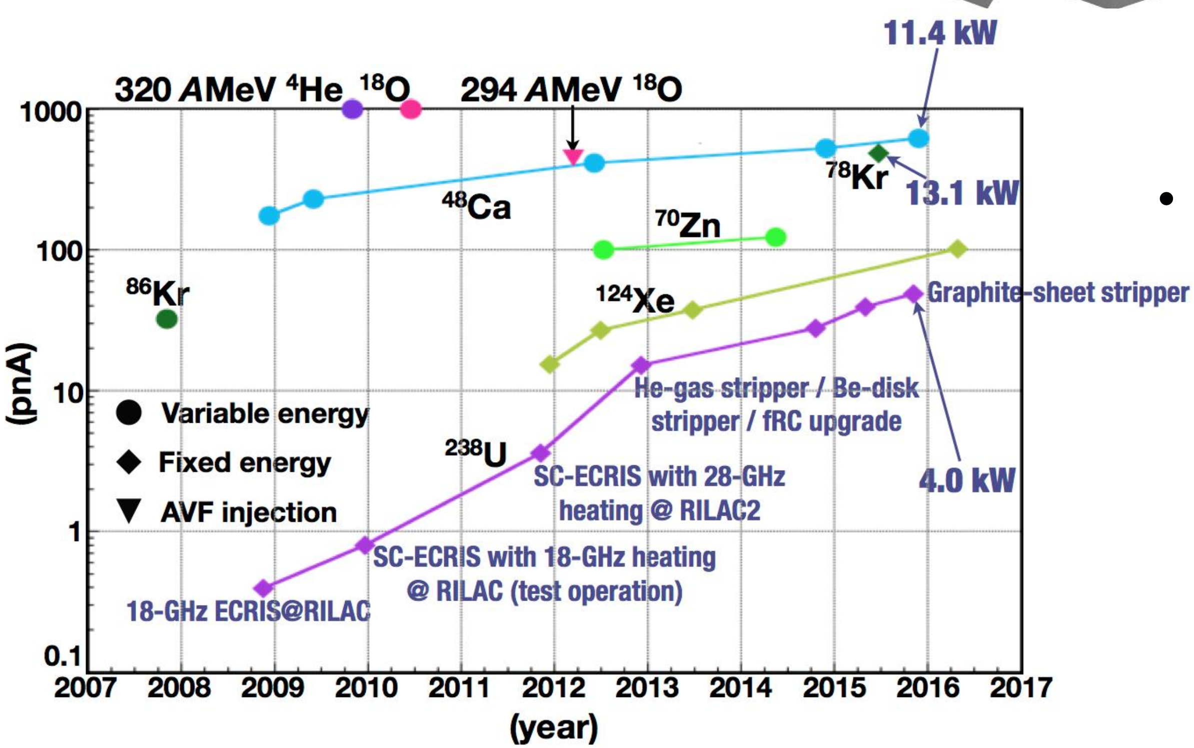
Superconducting Ring Cyclotron

BigRIPS
In-flight fragment Separator

Aimed at making significant progress in the studies of exotic nuclei far from stability

RIBF Accelerator Complex





- Deuteron ~ U ions
  E= 345 MeV/nucleon

- Max beam power ~ 13kW for Kr & Ca

in 2016

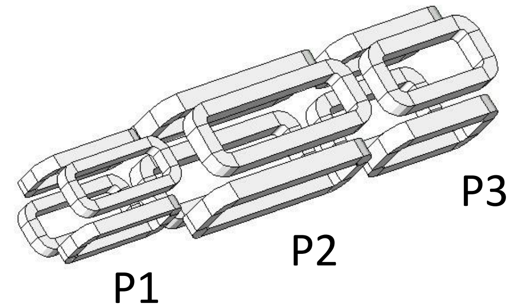
1st STQ (Superconducting Triplet Quadrupoles)

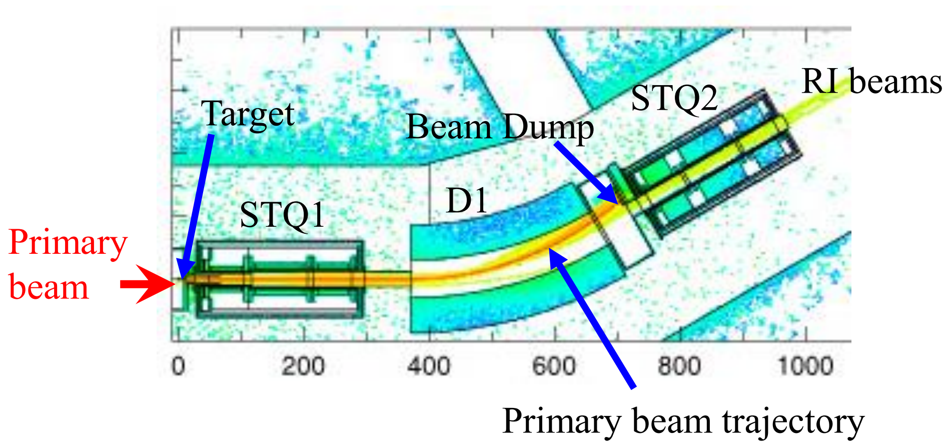
- Air-Core type superconducting triplet Quads

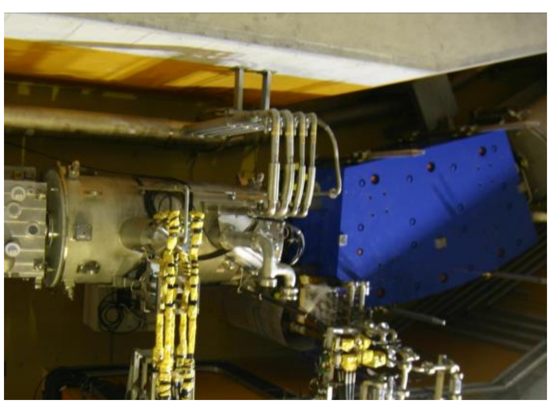
  Triplet in Single Cryostat   LHe Bath Cooling

- in the close proximity of the production target

- exposed to very high radiation

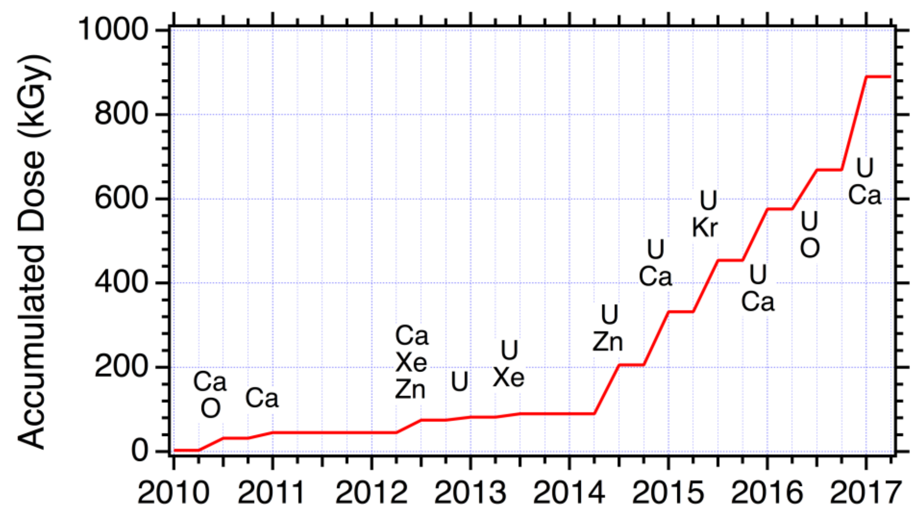






Dose accumulated ~ 890 kGy

In 9-years operation

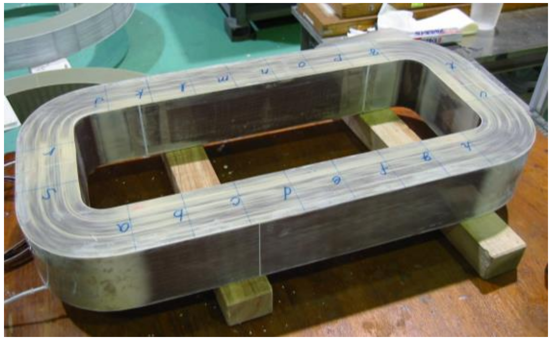


Operational experiences related to radiation effects

Operation data

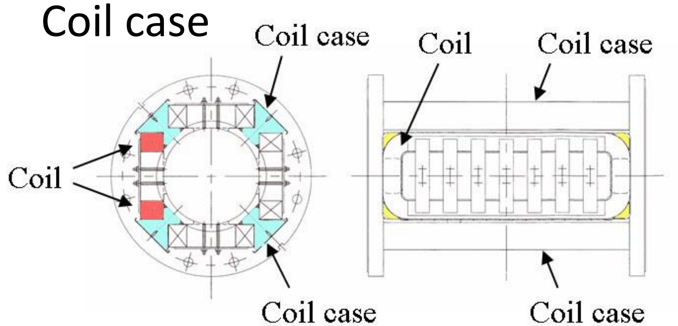
STQ1 Superconducting Triplet Quadrupoles

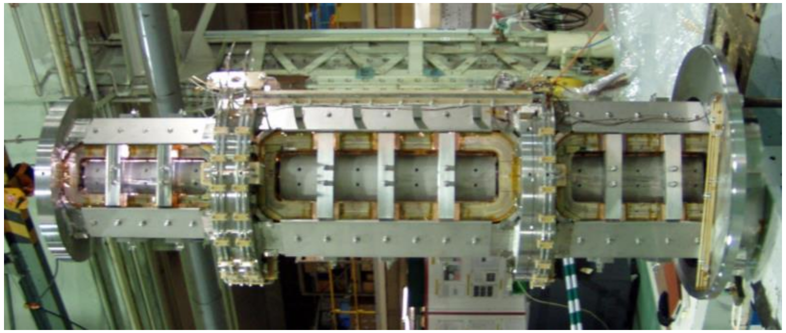
- NbTi superconducting Coils with Cu stabilizer
  PEI Insulated conductor 1.46 x 2.36 mm
  54 filaments with ϕ175 μm
  Cu/super ratio 1.33 Ic [A] 2100A @ 7T



- Flat Racetrack Coil
  -Wet winding
  - "layer by layer"
  -Epoxy Resin with Fillers
  most radiation sensitive material

- Supported in Coil case

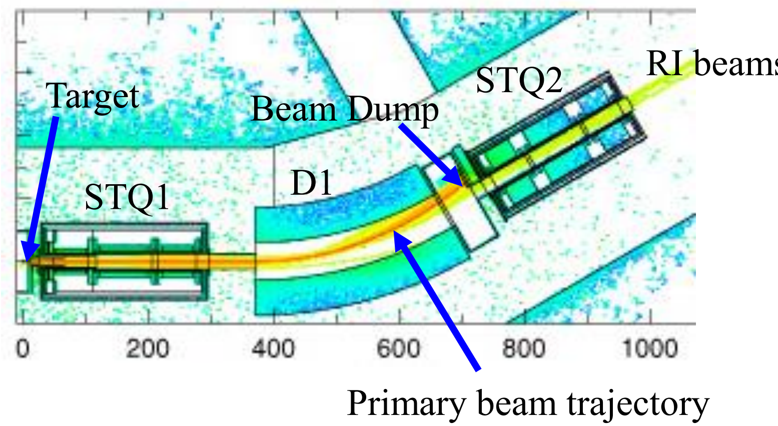




4K total cold mass ~ 3.5 tons in LHe bath (1000L)

	P1	P2	P3
Effective length [m]	~ 0.5	~0.8	~0.5
Field Gradient [T/m]	24	20	20
Number of turns	745	1315	1315
Ampere turn [kA]	552	825	825
Nominal current [A]	740	628	628
density [A/ mm^2]	188	159	159
Max field at coil [T]	6.0	6.9	7.0
Tc [K]	6.7	6.3	6.3
Ic/Iop	3.7	3.5	3.4
Stored energy [MJ]	0.34	1.21	0.81

Observed Beam Heat load



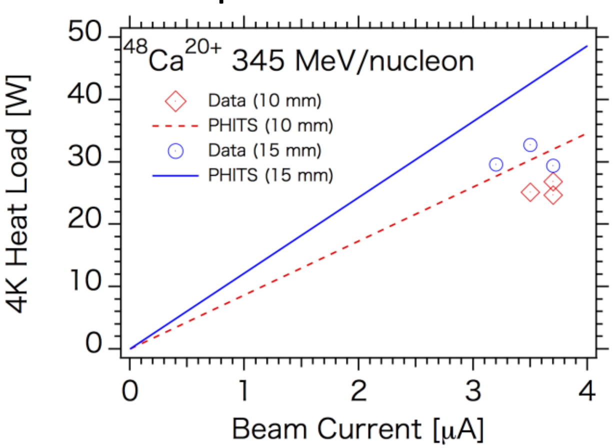
- Heat load to STQ1 cryostat caused by radiation
- 1st Observation
  Dec. 2008 $^{48}Ca^{20+}$ 345MeV/u + Be 15, 20 mm
  10~40 W for 0.5~2.3 μA
- 2010 - 2014
  $^{18}O^{8+}$ 345MeV/u + Be 60 mm
  $^{48}Ca^{20+}$ 345MeV/u + Be 10, 15 mm
  $^{70}Zn^{30+}$ 345MeV/u + Be 10 mm
  $^{124}Xe^{52+}$ 345MeV/u + Be 4 mm
  $^{238}U^{86+}$ 345MeV/u + Be 3 mm

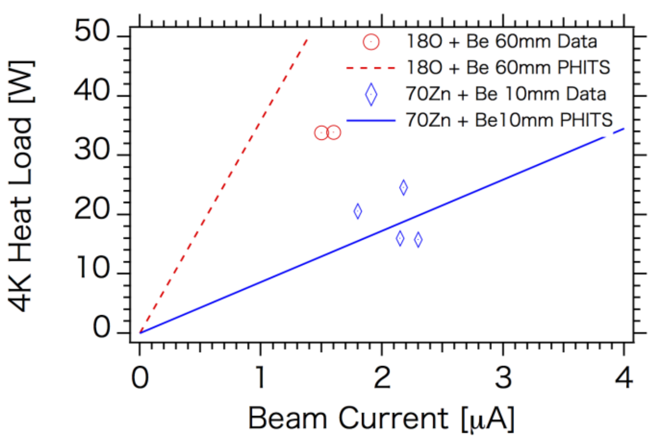
Typical Beam Current ~ 0.5 ~ 4 μA

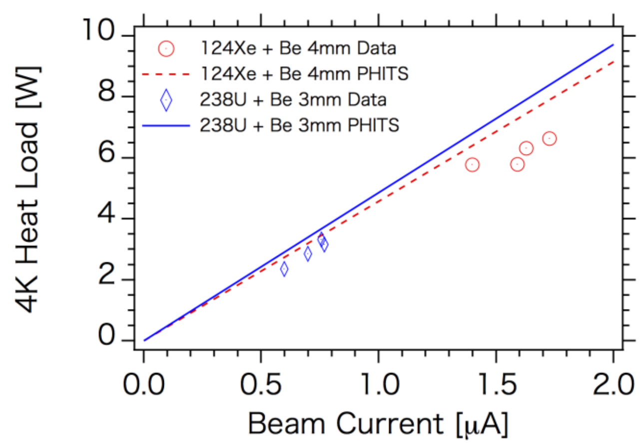
Beam Power ~ 7 kW

Observed Heat load 4 ~ 40 W

- Comparison with radiation transport calc. by PHITS simulation code







Simulation results agree within factor of ~2 In a wide range of mass A = 18 ~ 238

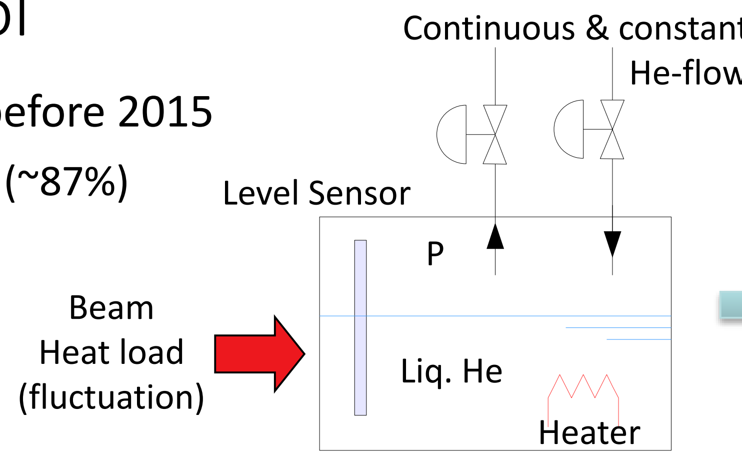
Cryogenic Control

- Cryo-control system before 2015

LHe level is kept constant (~87%)
by varying heater power

Heater Control

Power	LHe level
Increased	> 87.1%
Decreased	< 87.0%



Worked well
with fluctuation of < 50W
10 % of cooling capacity

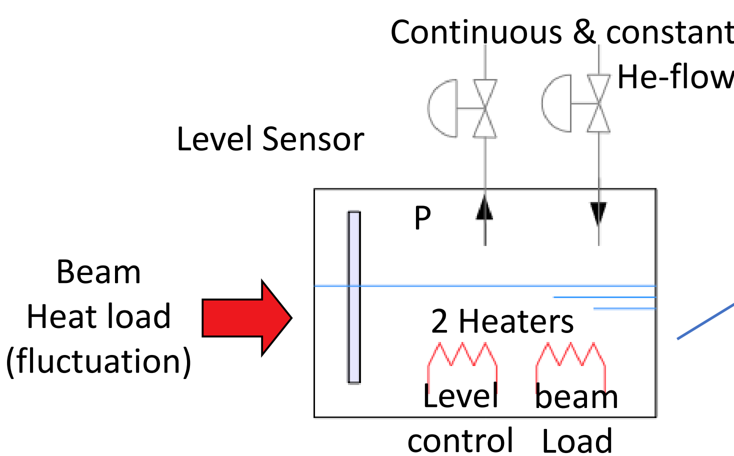
Heat load is evaluated
by comparing ave. heater powers

Intense ^{48}Ca Beam (~8 μA, 6.6 kW) + Thick Target (~20mm) Dec. 2014

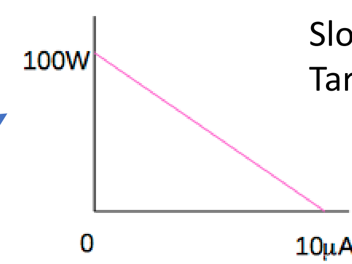
→ Large Beam Heat load ~80W > 15% of Cooling Capacity

Too large heat load fluctuation → Rapid increase of cold return gas makes Cryogenic system unstable

- Introduce "beam load heater"



Beam Load Heater
Output

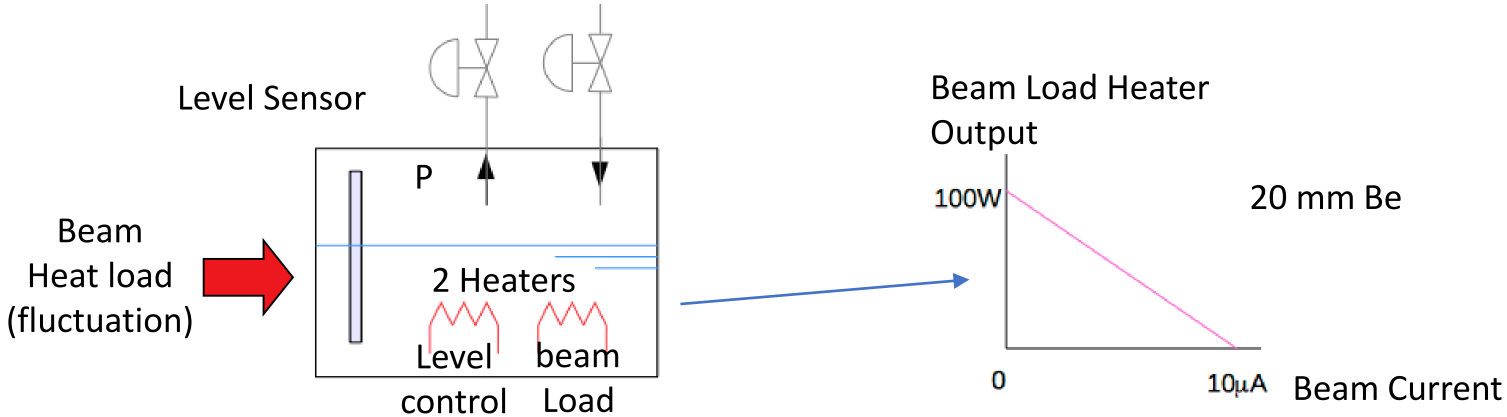


Slope depends on
Target thickness

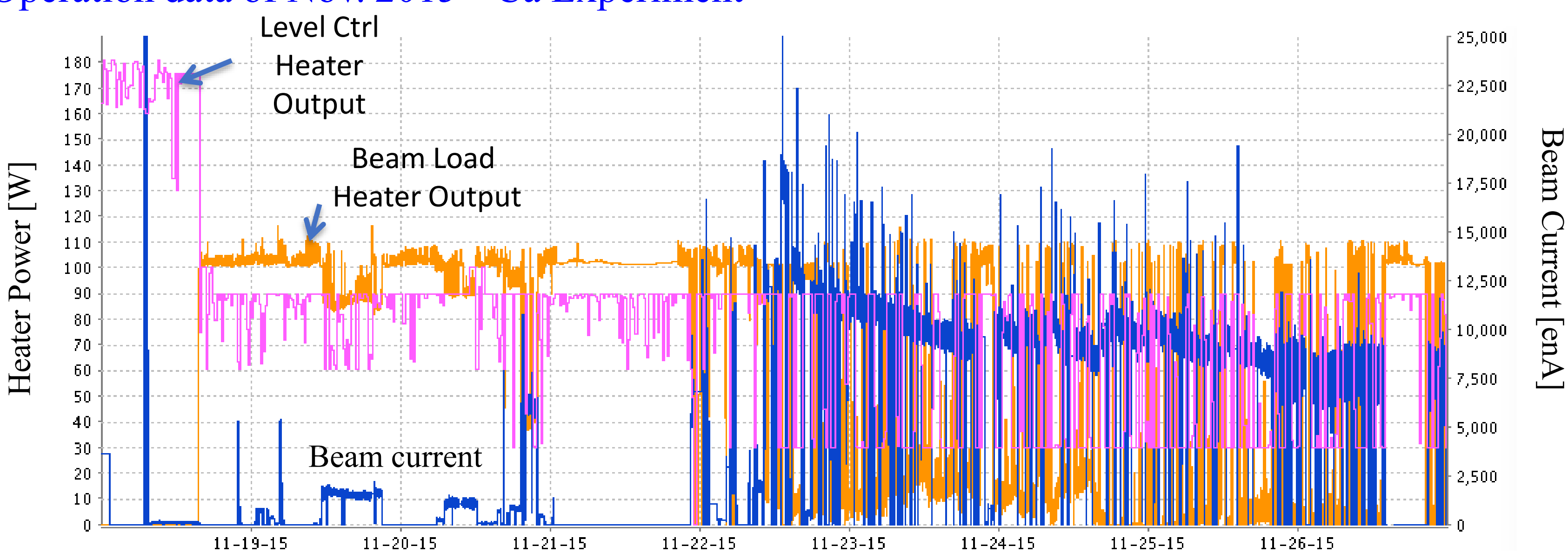
Beam Current

Compensate beam heat load fluctuation

Beam Heat load with Upgraded Beam Intensity



Operation data of Nov. 2015 ^{48}Ca Experiment

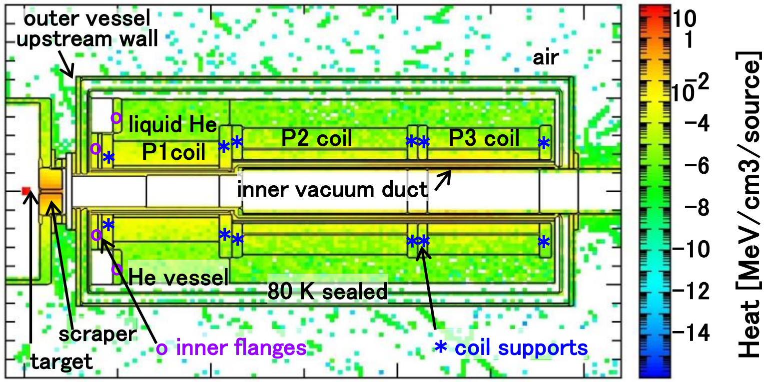


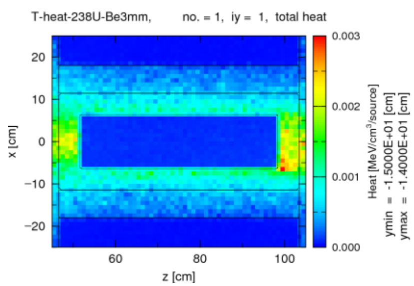
Observed max beam heat load of 170 W (^{48}Ca with 20 μA + 20 mm Be target) in 2016

1/3 of cooling capacity

Dose Estimate

PHITS simulation   Local Heat Deposit





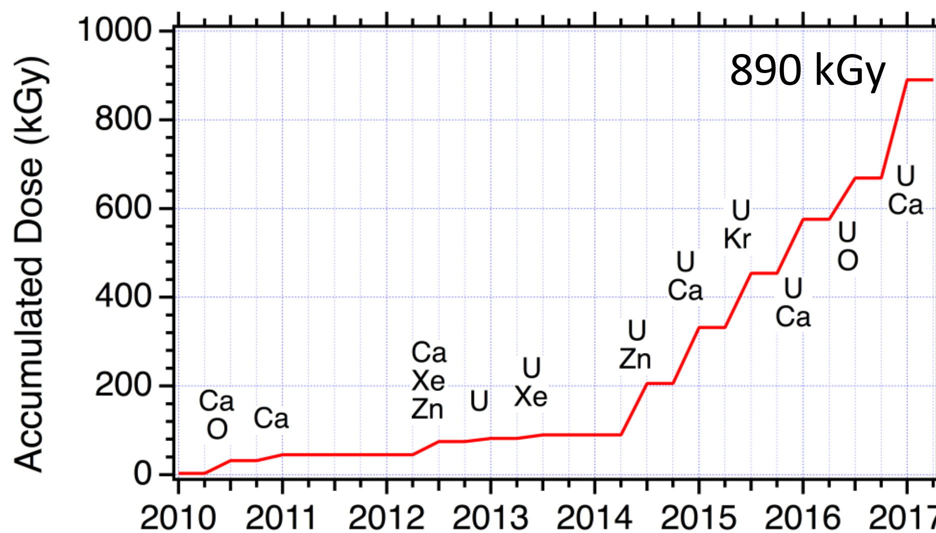
Max density
@ P1 coil

Beam	Target Thickness (mm)	Heat deposit density (mW/cc)
$^{18}O^{8+}$	20	0.45
$^{48}Ca^{20+}$	30	3.5
$^{70}Zn^{30+}$	12	3.5
$^{78}Kr^{36+}$	7	2.0
$^{238}U^{86+}$	4	20

per 1 p μ A

Operation Record

Season	Beam	Target Thickness (mm)	Integrated Current (p μA day)	Dose (kGy)
2014 2Q	$^{238}U^{86+}$	1, 3, 4, 7	0.3	43
	$^{70}Zn^{30+}$	5, 8, 10, 12, 17	1.1	33
2014 4Q	$^{238}U^{86+}$	4, 5, 6, 7	0.1	30
	$^{48}Ca^{20+}$	12, 15, 20, 30	3.8	85
2015 2Q	$^{238}U^{86+}$	1, 3, 4, 5	0.3	44
	$^{78}Kr^{36+}$	7, 10	3.4	83
2015 4Q	$^{238}U^{86+}$	2, 5, 7	0.2	60
	$^{48}Ca^{20+}$	15, 20	2.9	62
2016 2Q	$^{238}U^{86+}$	2, 4, 5, 7	0.4	77
	$^{18}O^{8+}$	15, 20	3.9	15
2016 4Q	$^{238}U^{86+}$	4, 7, 10	0.2	49
	$^{48}Ca^{20+}$	15, 20	6.8	172



Observed Impurities in He gas form STQ1 cryostat

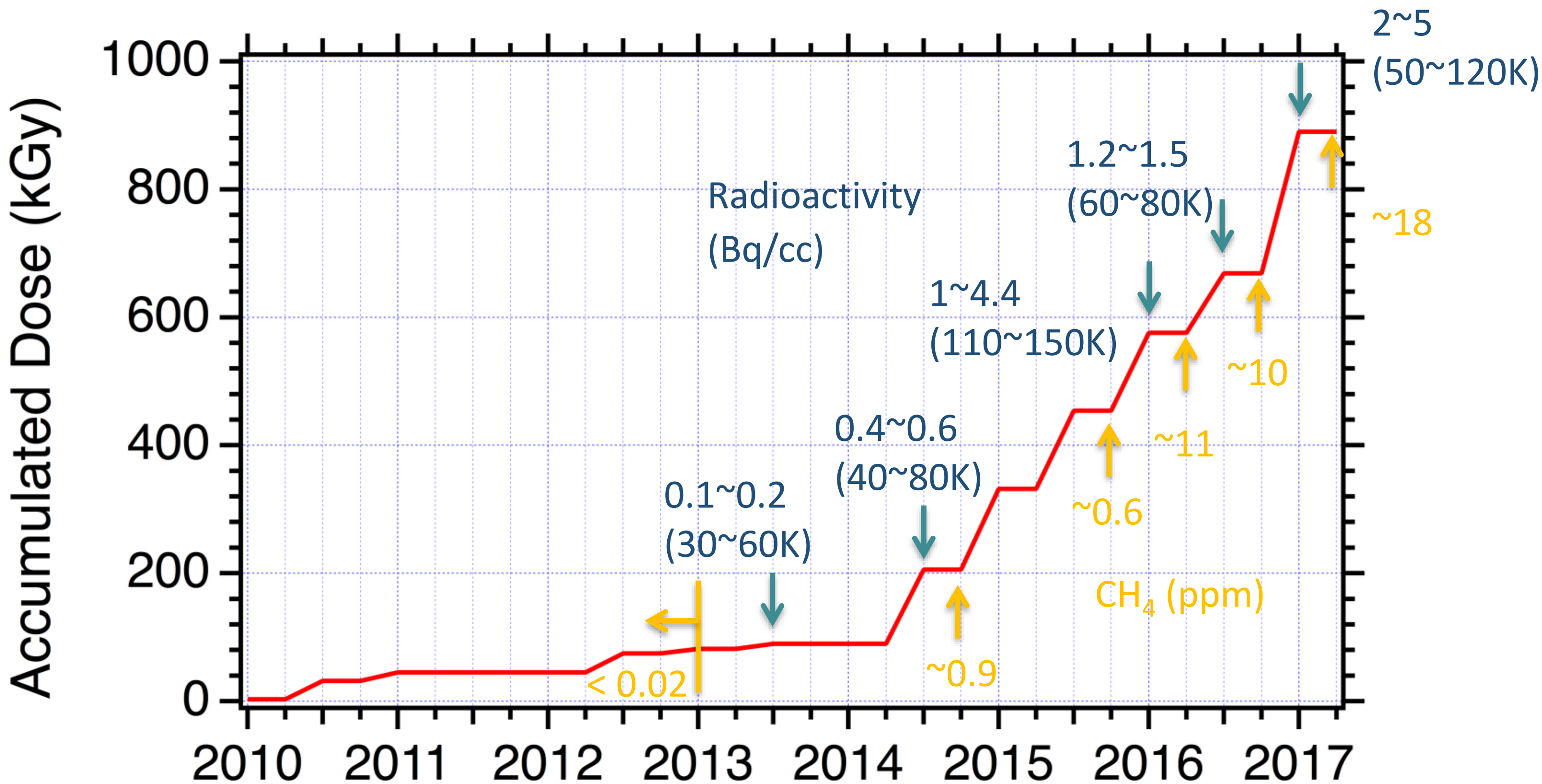
- Tritium(T) — ^{4}He(n,d)T (E_{th}=22MeV) reaction in LHe bath

  Radioactivity in vent gas from STQ1 cryostat at warm-up monitored by Gas-monitor ALOKA MGR-133

- Hydrocarbon (CH_4) — Dissociation of epoxy ?

  CH_4 concentration in He gas at discharge line of compressor by Gas Chromatograph

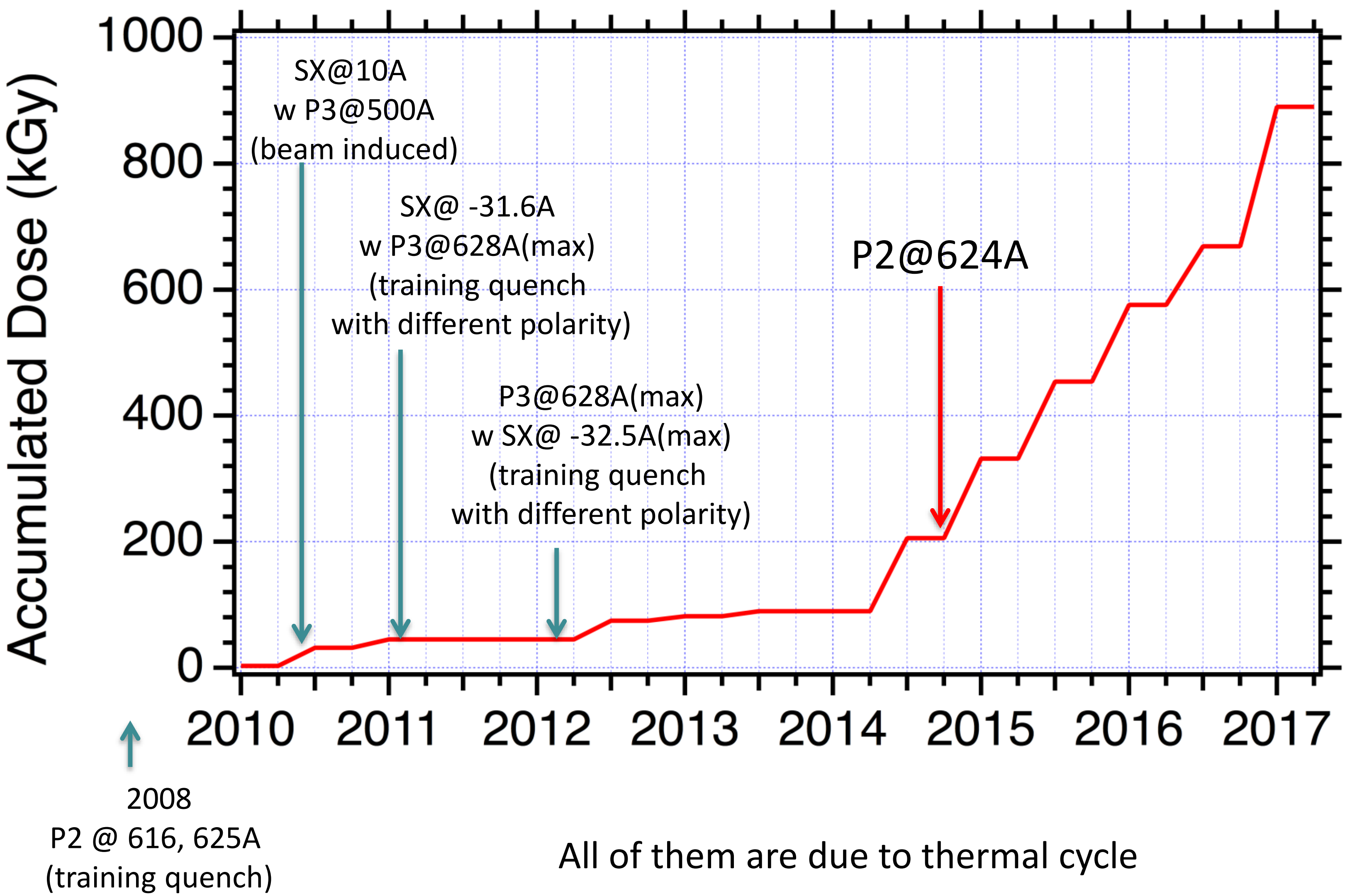
  Observed when start circulating He gas in STQ1 cryostat at pre-cooling or purification



Quench Records & Accumulated Dose

5 quenches : P2, SX, P3 coils

P1 coil never quenched



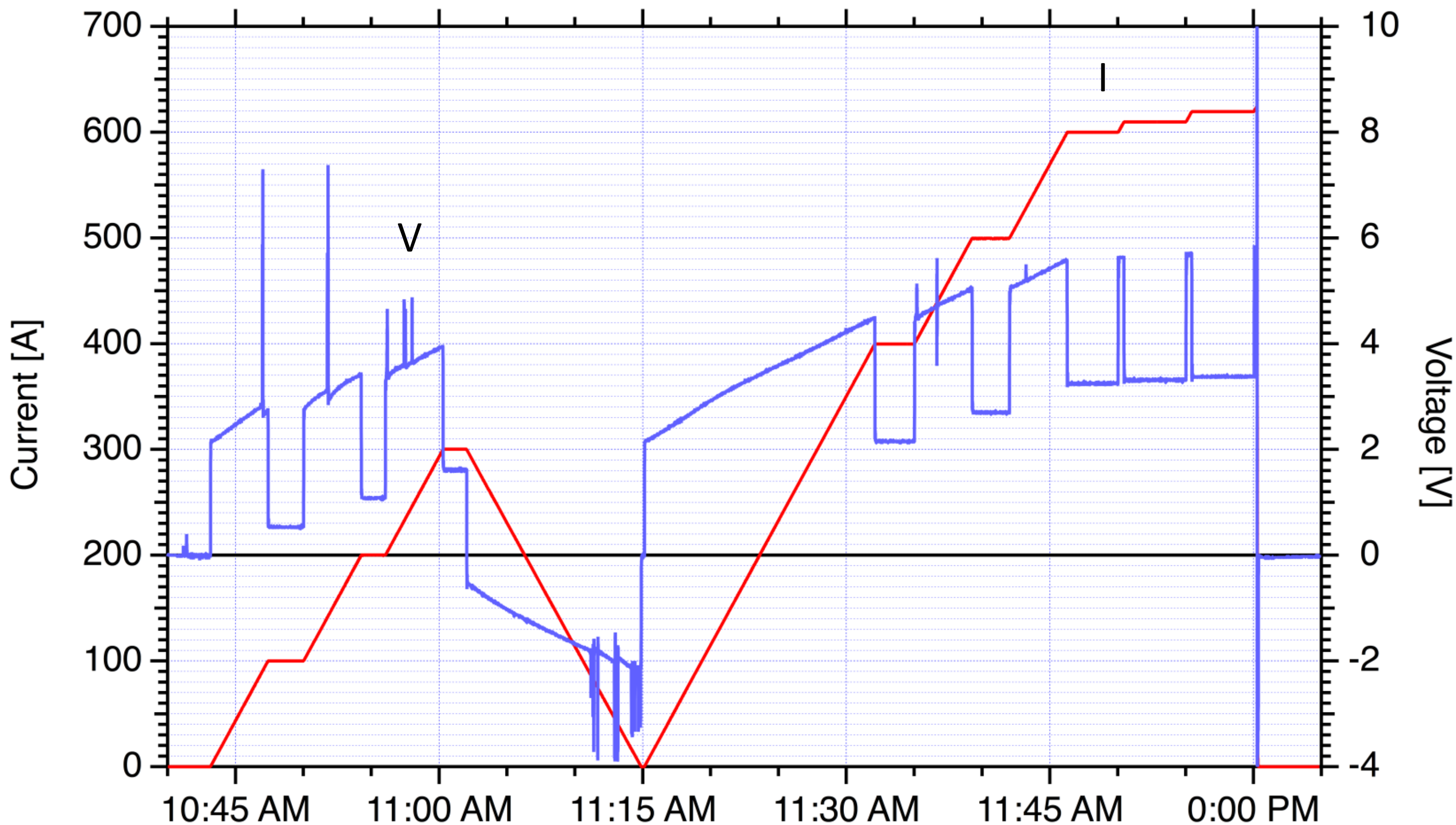
All of them are due to thermal cycle

Excitation voltage of P2 quench ramp

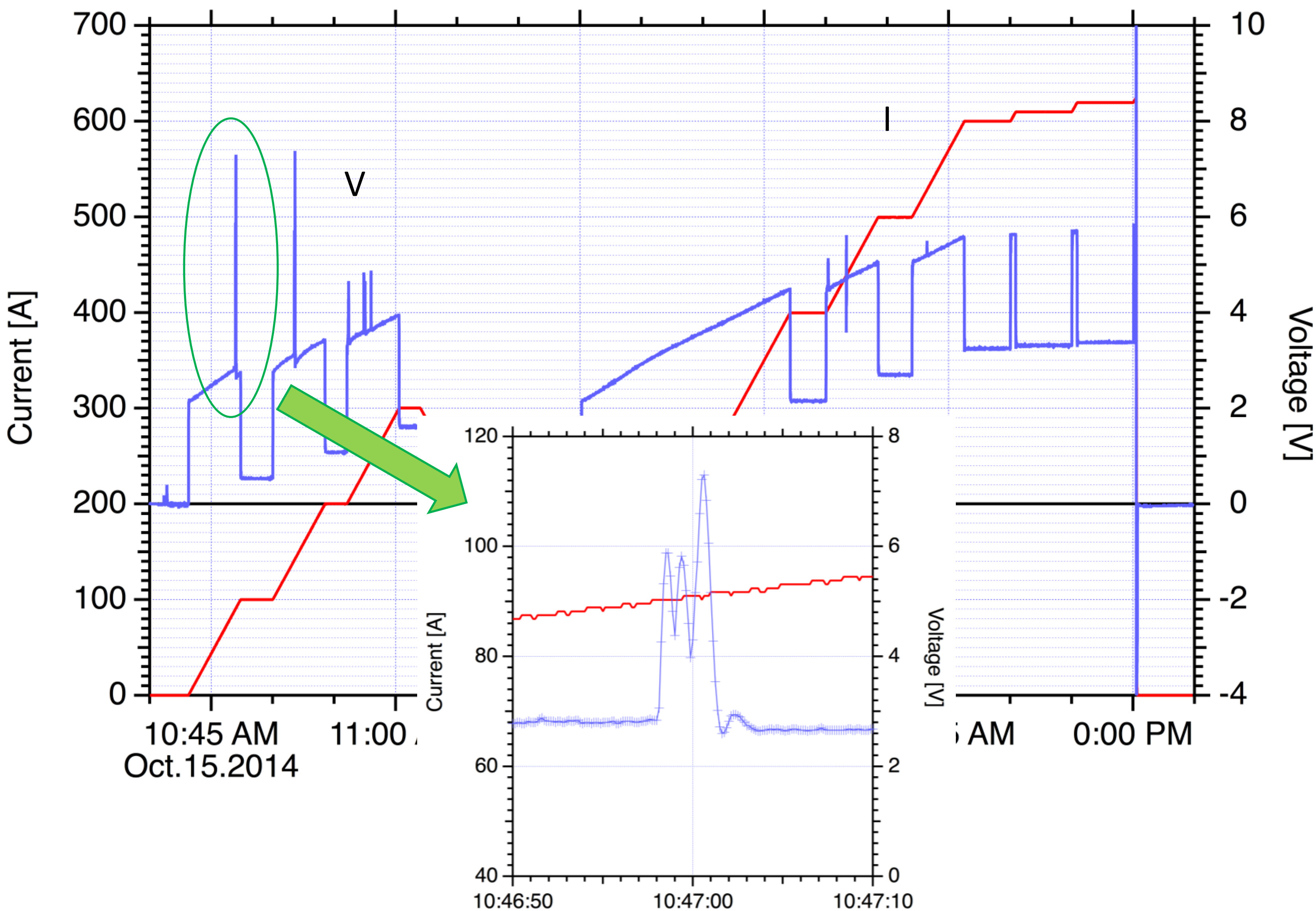
Oct. 15 2014 (~200kGy) First ramp after pre-cooling

- Stepwise ramp-up with ramp rate 0.4A/s
  - 100A step (<600A), 10A step (>600A)
- Operation log data
  - Analog monitor output of PS
  - Sampling speed of 125msec

Quench @ 624A
(max 628A)

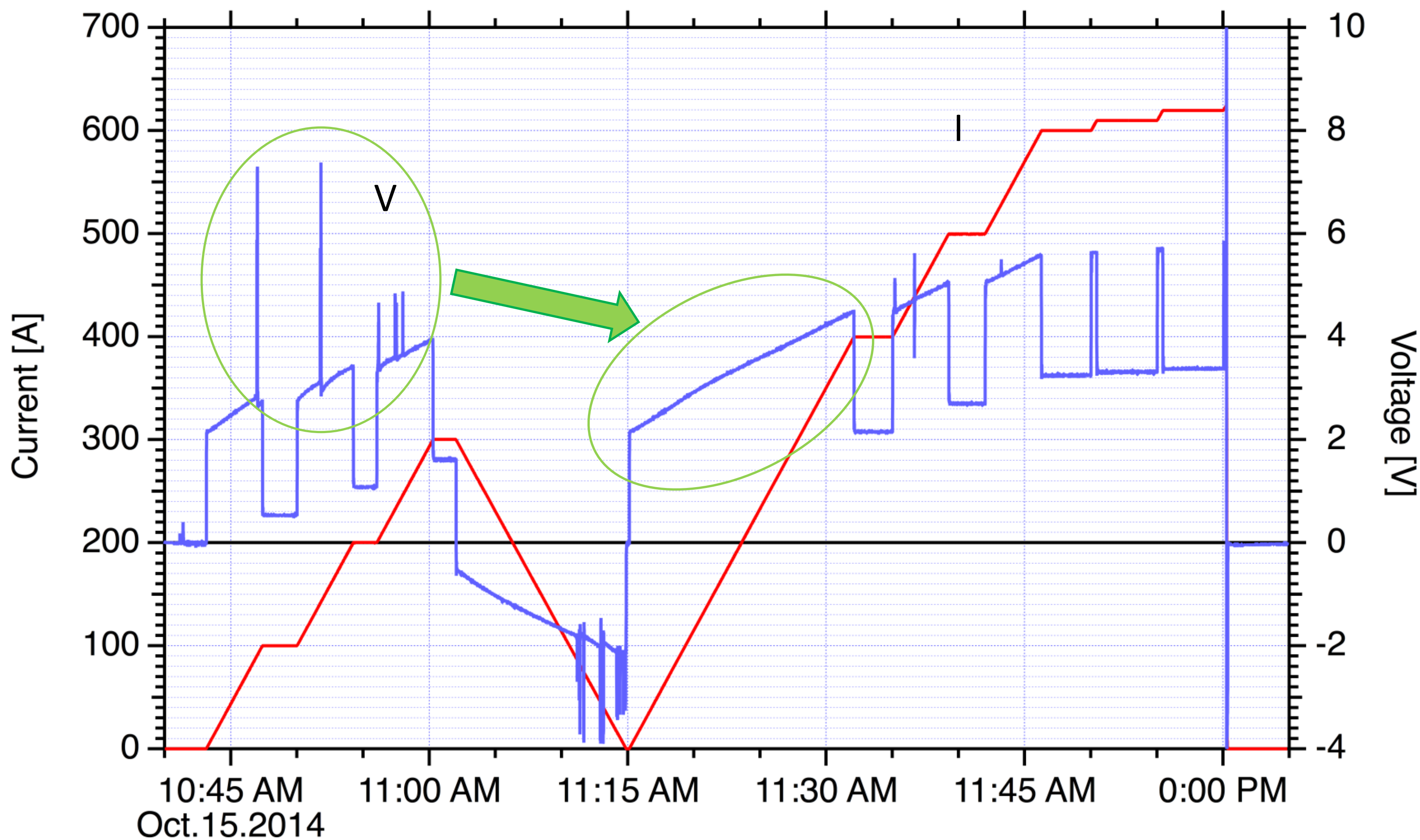


Spikes in excitation voltage



Spikes in excitation voltage @ 90A

Spikes in excitation voltage



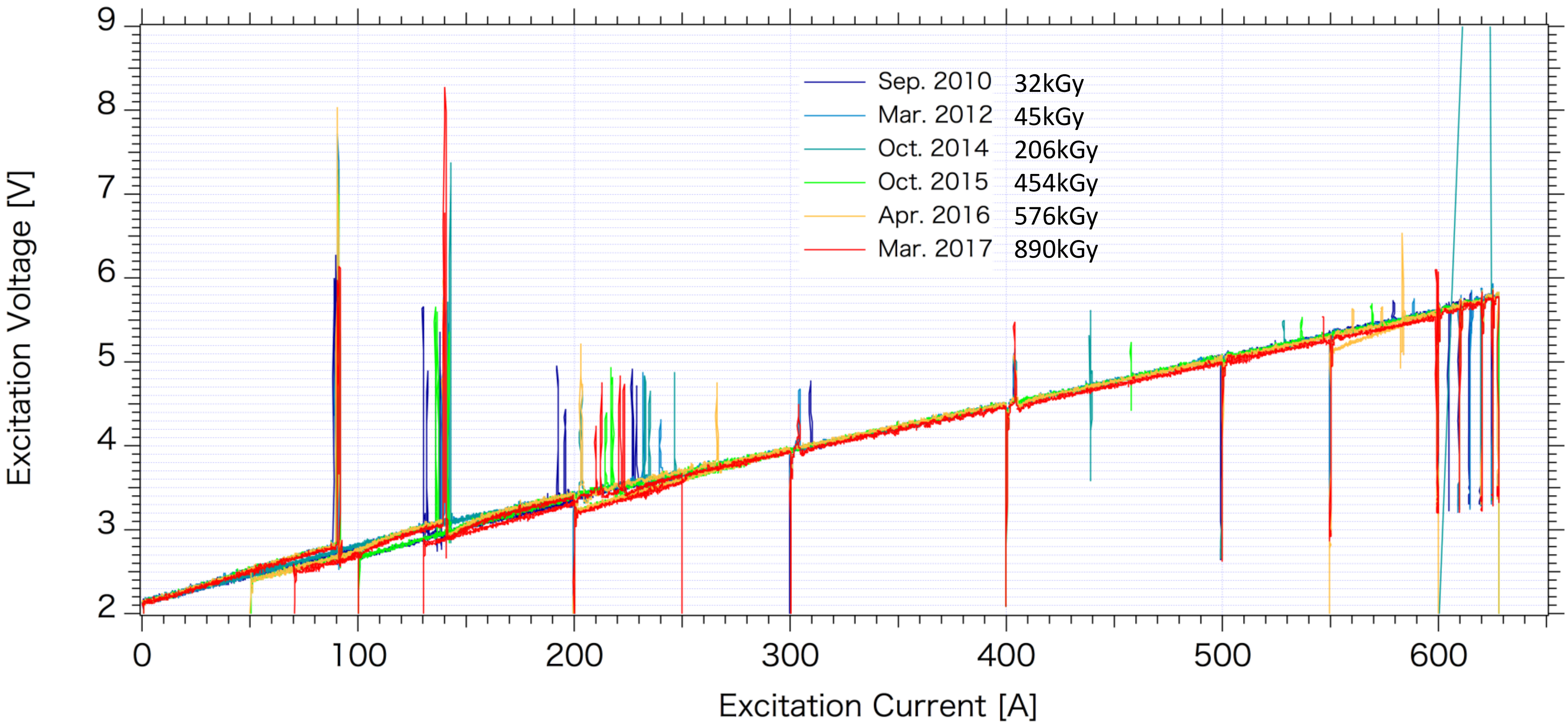
Spikes disappeared in 2nd ramp-up

Coil movement due to thermal cycle

Can we see difference between ramps in different accumulated dose periods ?

Comparison of different ramps

V vs I plot of 1st P2 ramp-up after pre-cooling



Slope : Voltage drop due to DC cables

Intercept : inductance of P2 coil (ramp speed 0.4 A/s)

No distinct difference between different ramps (different dose)

No signal of degradation

Smaller disturbance may be detected with faster logging system

Summary

- Beam Heat load to Cryostat

  Evaluated by heater power analysis of operation data of BigRIPS cryogenic system

  PHITS simulation results agree within a factor of 2

- Dose Estimate

  Operation records (beam current) & Local heat deposit estimated by PHITS simulation

  Accumulated dose of STQ1 coil : order of 1 MGy (890kGy)

- Excitation voltage as coil motion

  No distinct difference between different ramps (different dose)

  No signal of degradation

- Impurities in He gas from cryostat

  Tritium and CH_4 in STQ1 cryostat increase, as the dose increases