SK-Gd報告

第7回極低放射能研究会

2021年3月25日

東京大学宇宙線研究所

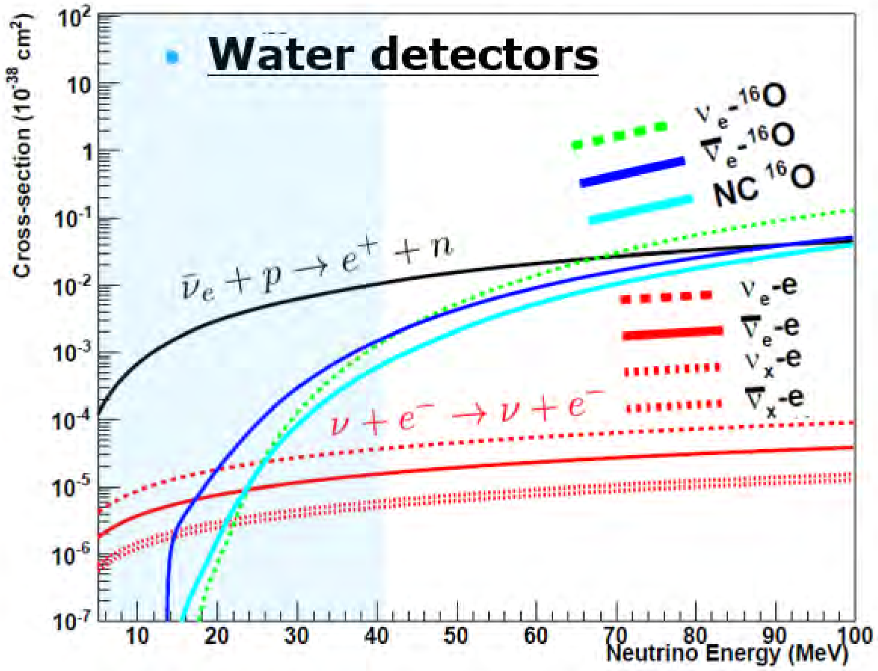
関谷洋之

内容

- SK-Gdの目指すもの
- SKへ導入した低放射能硫酸ガドリニウムとその評価方法
- 2020年7月14日～8月17日に行ったGd導入の様子
- 導入したGd濃度の確認
- Gdによる中性子捕獲イベントの紹介
- 導入後の様子（Dark noise、バクテリア？、LowE BG）
- 今後とまとめ

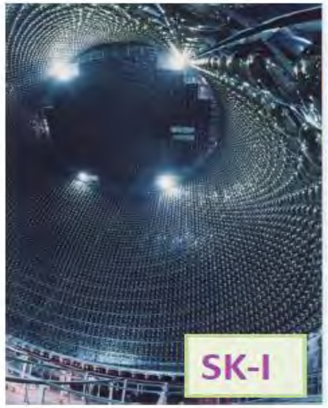
Super-Kamiokande VI

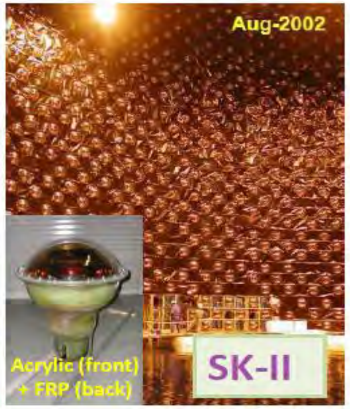
- Ring imaging Gd-doped water Cherenkov detector
  - **49468 tons of pure water with 5426kg of Gd**
  - 11129 50cm PMTs for Inner detector
- 1km (2700 mwe) underground in Kamioka
- Most sensitive to $\bar{\nu}_e$ through inverse beta decay, and the emitted neutron can be tagged with more than 50% efficiency.

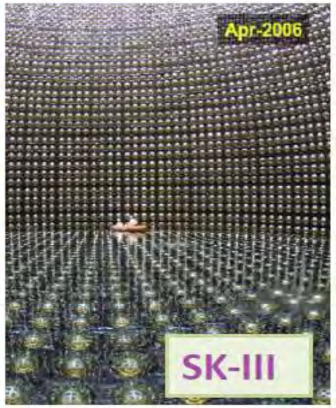


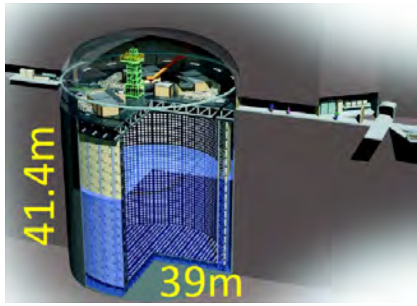
1996 2002 2006 2008 2018 **2019 2020**

SK-I | SK-II | SK-III | SK-IV | SK-V | SK-VI

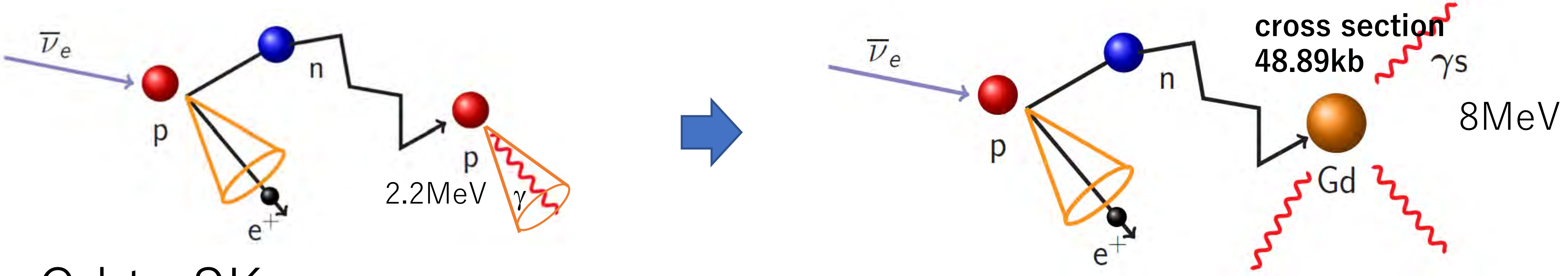




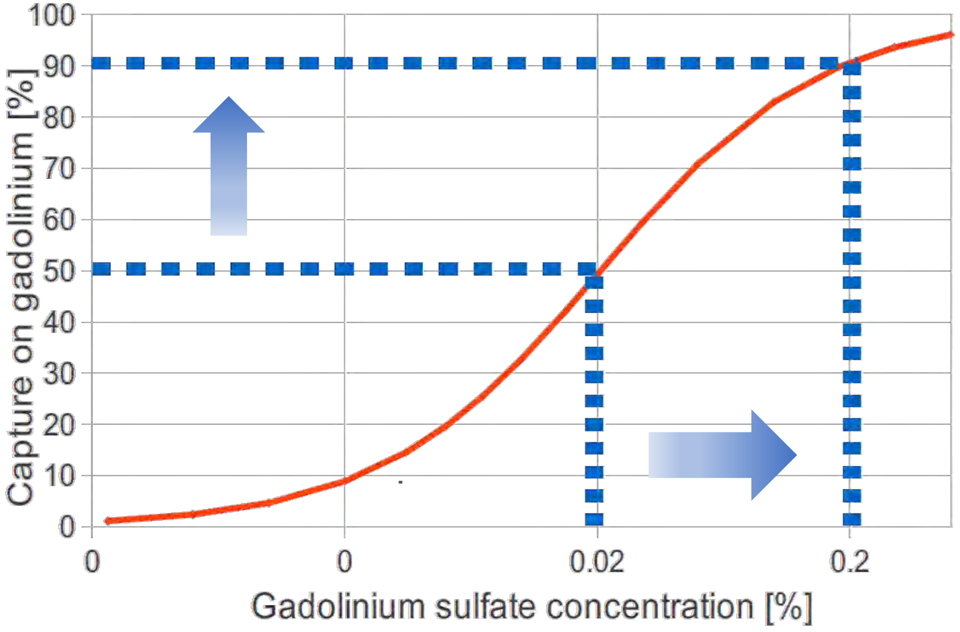




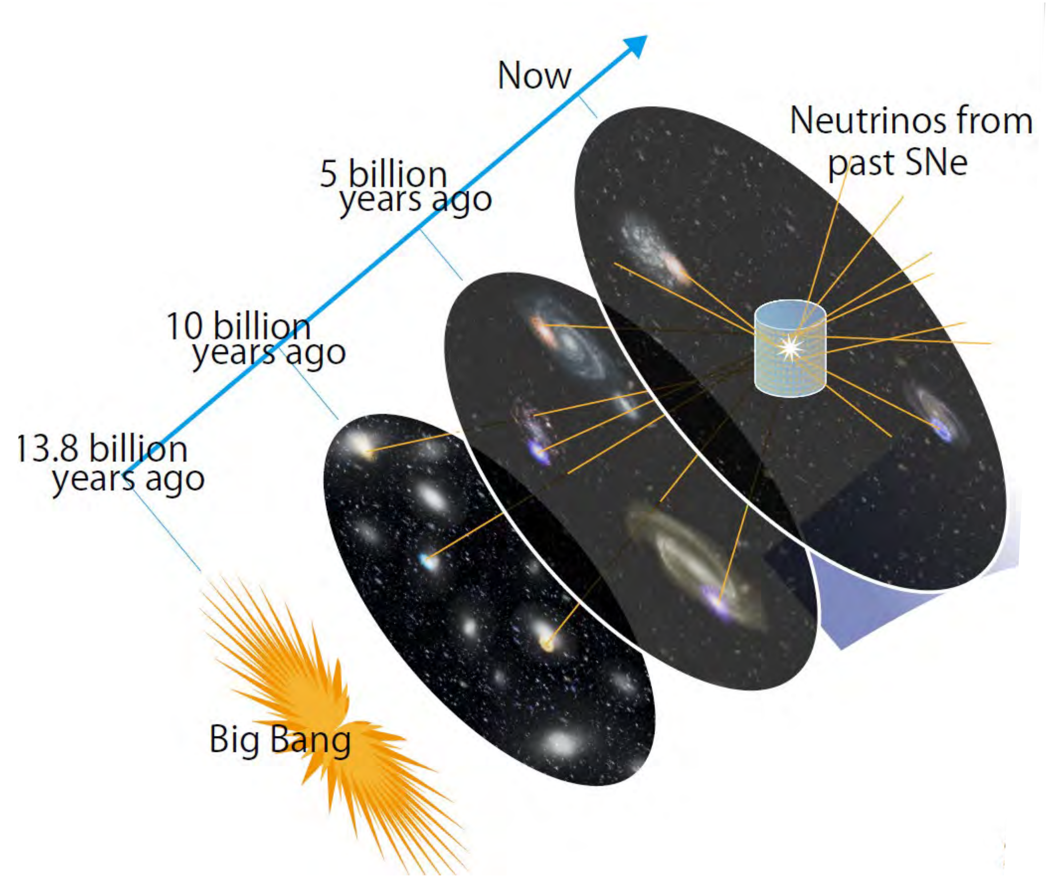
SK-Gd project



- Loading Gd to SK
  - To significantly enhance detection capability of neutrons from $\bar{\upsilon}$ interactions
  - 0.02% $Gd_2(SO_4)_3$ concentration for the 1^{st} step
    - About 50% of neutron would be captured by Gd, enhancing neutron tagging efficiency by 2-3 times.
- Planned gradual increasement of Gd
  - Final target: 90% of neutron tagging
  - Aiming at 75% with this Kakenhi



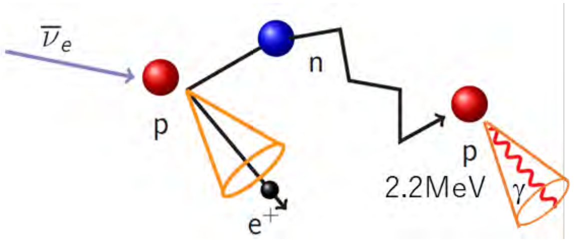
Diffused Supernova Neutrino Backgrounds
Supernova Relic Neutrino



- Neutrinos produced from the past SN bursts and diffused in the current universe.
  - ~ a few SN explosions every second → $O(10^{18})$ SNe so far in this universe
  - Can study history of SN bursts with neutrinos

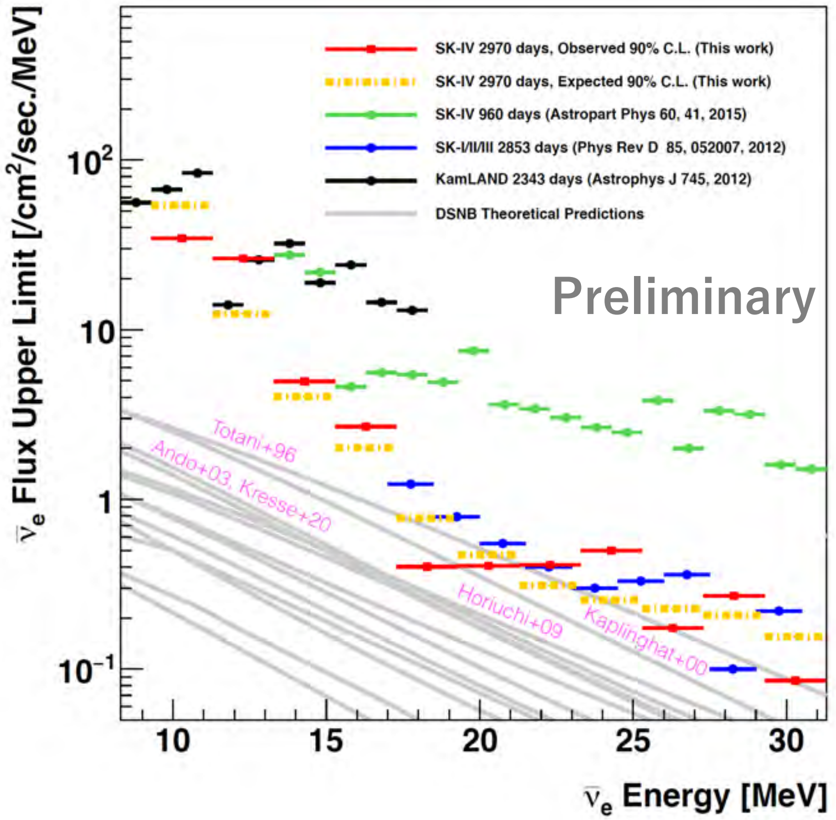
$$\frac{dF_\nu}{dE_\nu} = c \int_0^{z_{max}} R_{SN}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu} (1+z) \frac{dt}{dz} dz$$

DSNB search in SK-IV

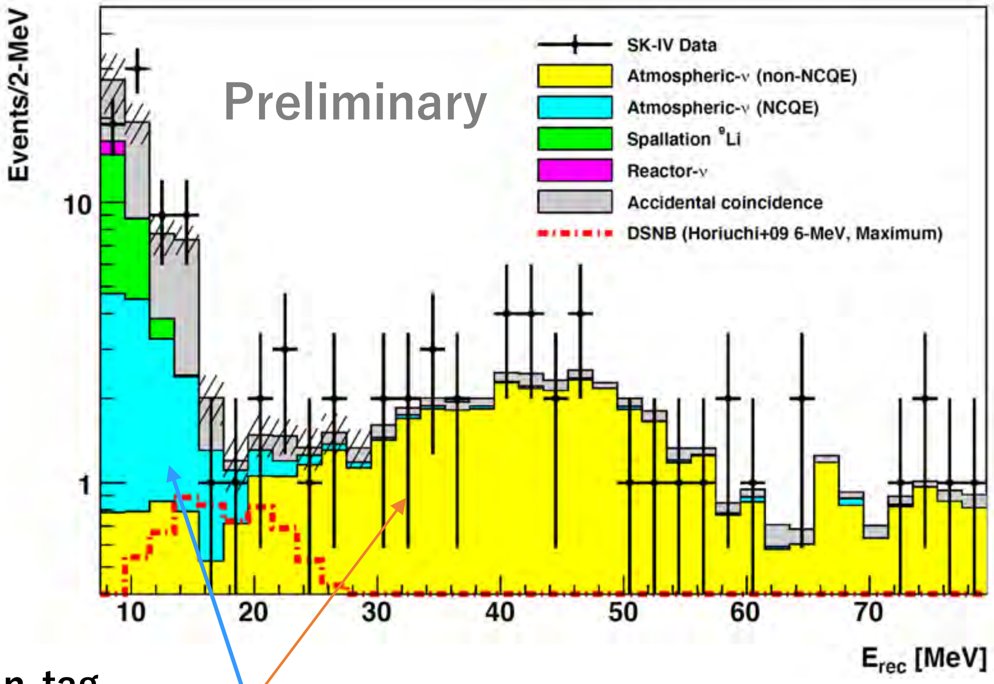


Already touched the predicted region!

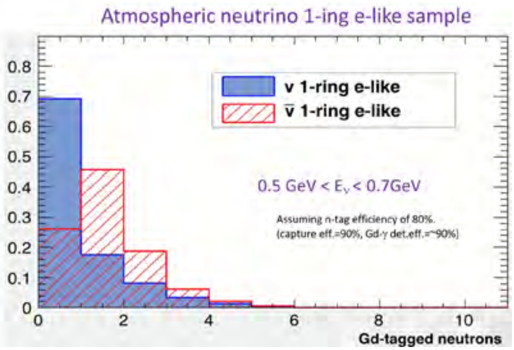
Pure water, with neutron tagging

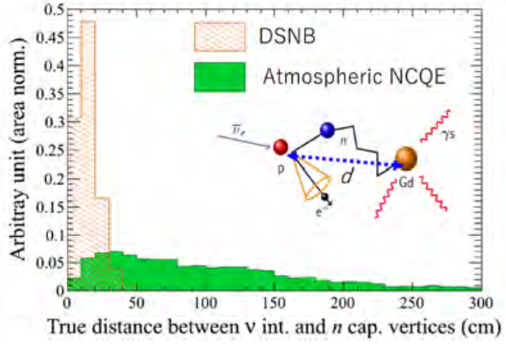


Pure water, with neutron tagging



With Gd n-tag,
Neutron multiplicity cuts and topology cuts will reduce these BG





SK-Gd sensitivity will cover many predictions !

Technologies for Low RI $Gd_2(SO_4)\cdot 8H_2O$

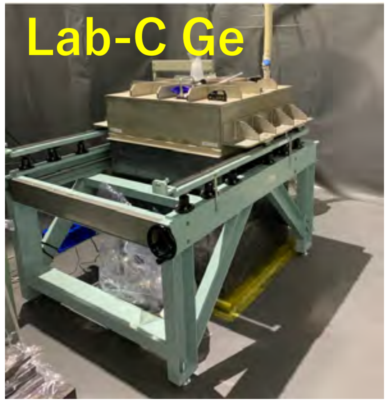
S.Ito, H.Ito, K. Ichimura et al.

ICP-MS

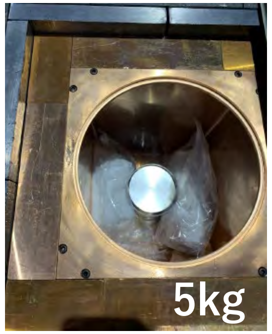
- Established the analysis of ^{238}U, ^{232}Th, and ^{226}Ra at ppt level

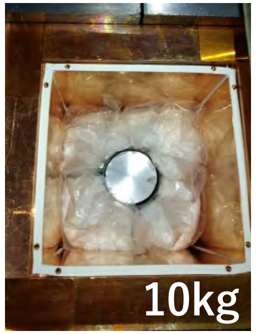
Ge

- Sensitivity of ~0.2 mBq/kg was achieved by increasing the sample weight
- Sensitivity of ~0.5 mBq/kg was achieved by applying the Ra disk analysis method.



Enlarged sample room





Ra-disk method

Ra captured resin disk after Gd sulfate solution passed

Another new Ge is under commissioning!

Requirement for 0.1%Gd-loading

Radioactive chain	Part of the chain	SRN (mBq/kg)	Solar-ν(mBq/kg)
^{238}U	^{238}U	< 5	-
	^{226}Ra	-	< 0.5
^{232}Th	^{228}Ra	-	< 0.05
	^{228}Th	-	< 0.05
^{235}U	^{235}U	-	< 30
	^{227}Ac/^{227}Th	-	< 30

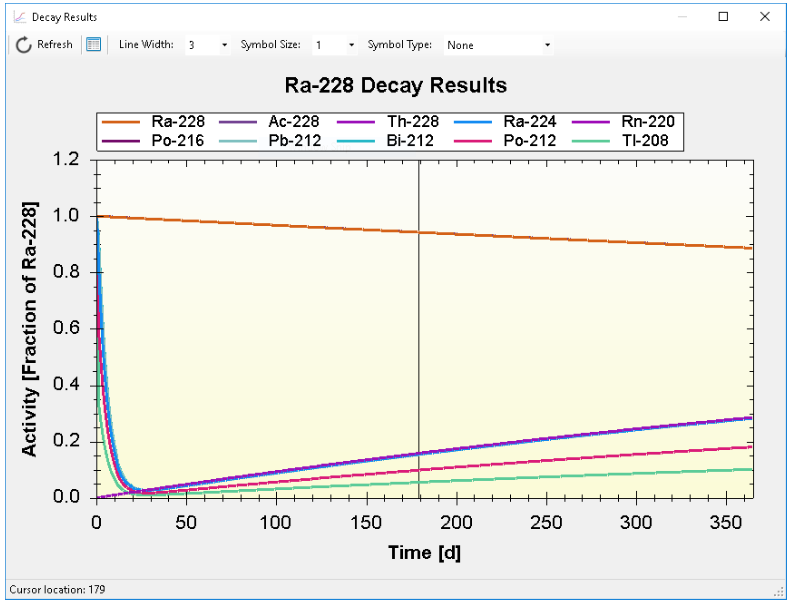
^{238}U < 0.5 mBq/kg →400 ppt
^{232}Th < 0.05 mBq/kg →13 ppt

N.B. We don't have methods to measure 0.05mBq/kg of ^{228}Ra

^{228}Ra Impact to Solar neutrino

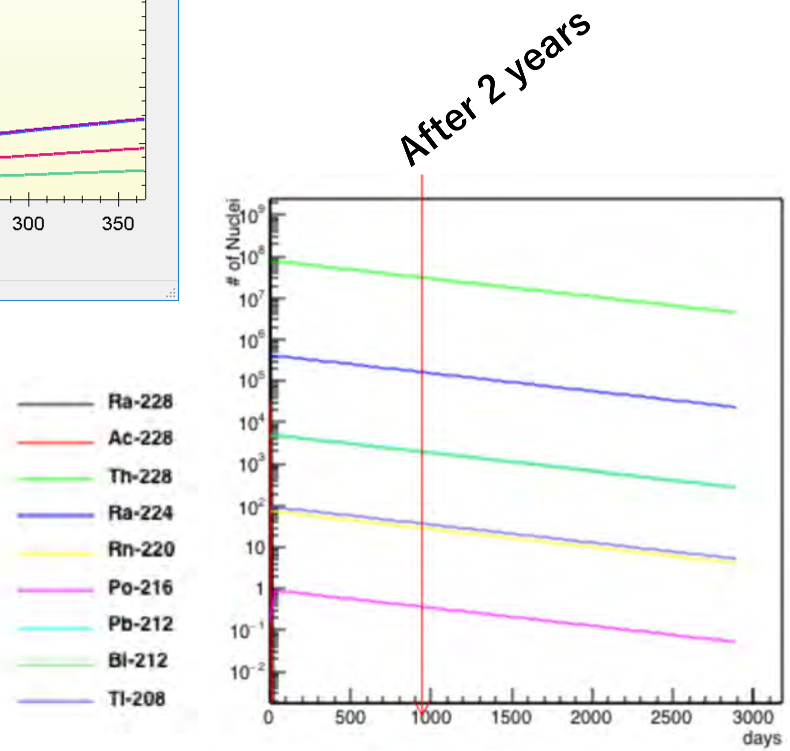
Ra is removed by water system, but Th is not

When Gd loaded one year had passed since its production and ^{228}Th had been produced about 1/3 of initial ^{228}Ra activity

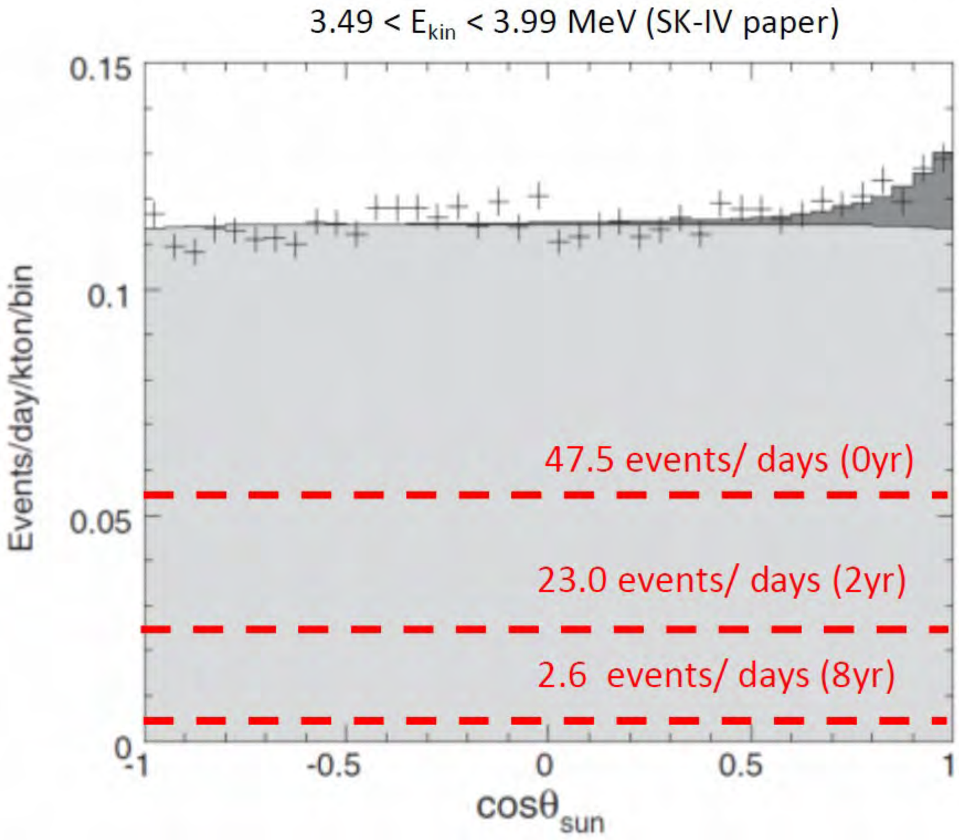


M. Thiesse

^{228}Th decays with half lifetime 2years



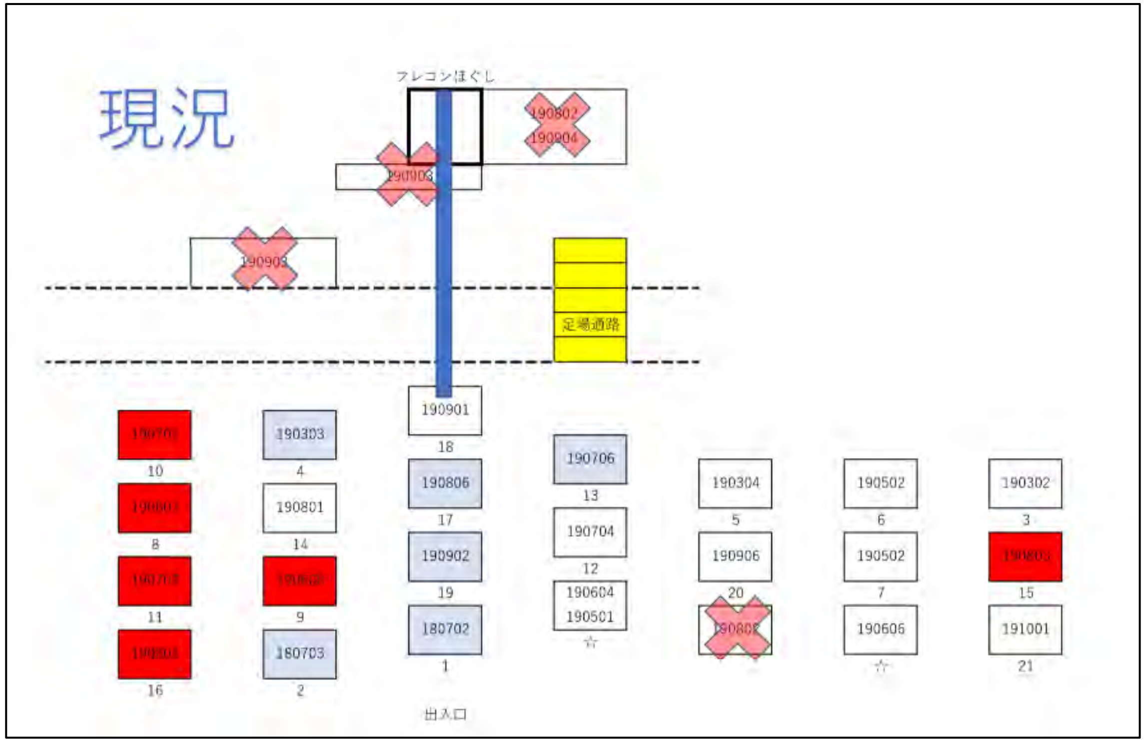
H.Ito

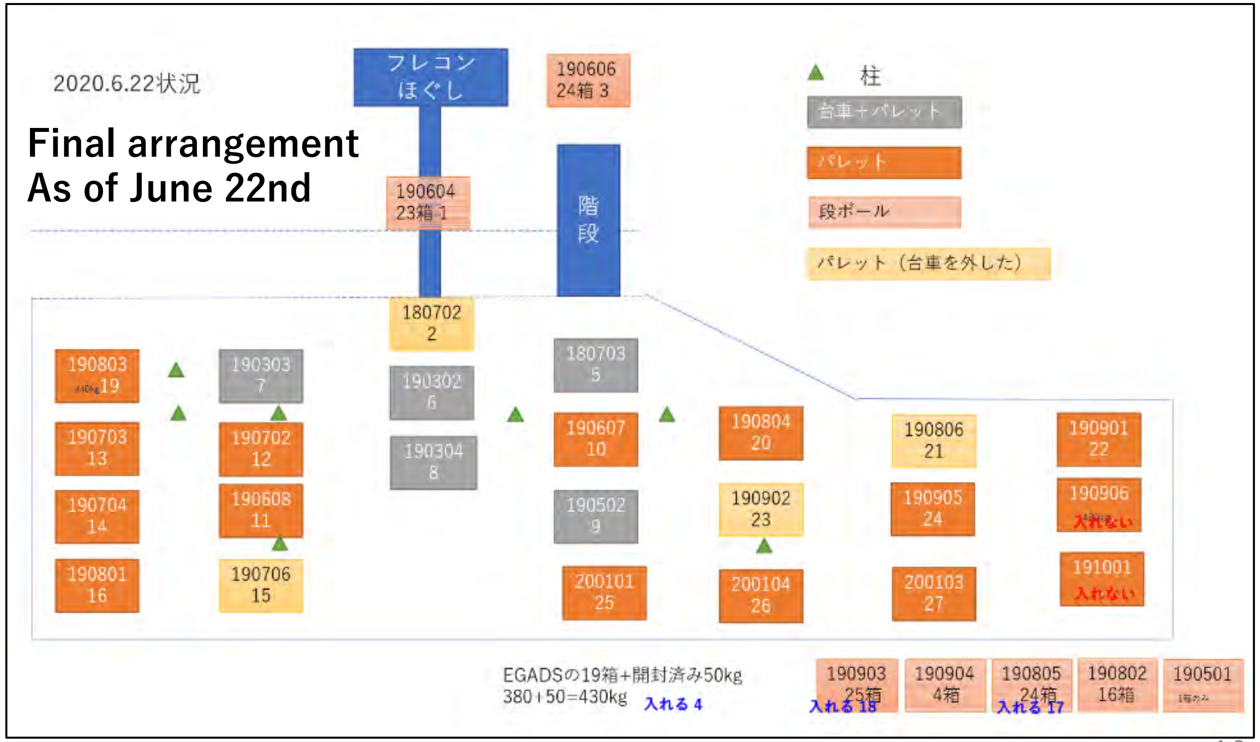


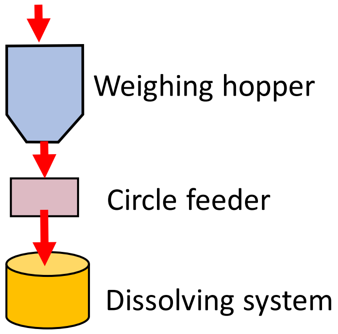
It might be acceptable.

Real Sokoban

To reject high Th powder and to track the RI
Re-ordering of 500kg x 26 containers was required



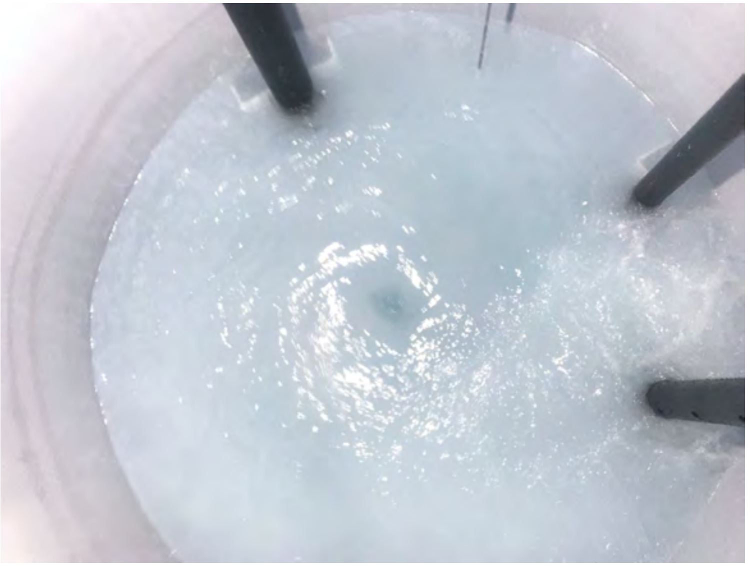




Direct supply with shovels and buckets

Pictures

Just after adding 8.2kg of $Gd_2(SO_4)_3 8H_2O$



10 minutes later

One sequence:
8.2kg(→8.7kg) of powder in 768L
30minues/cycle

The record

On Aug 17

finished loading 13212 kg of

"$Gd_2(SO_4)_3 \cdot 8H_2O$+2.5% water"

=12884kg of $Gd_2(SO_4)_3 \cdot 8H_2O$

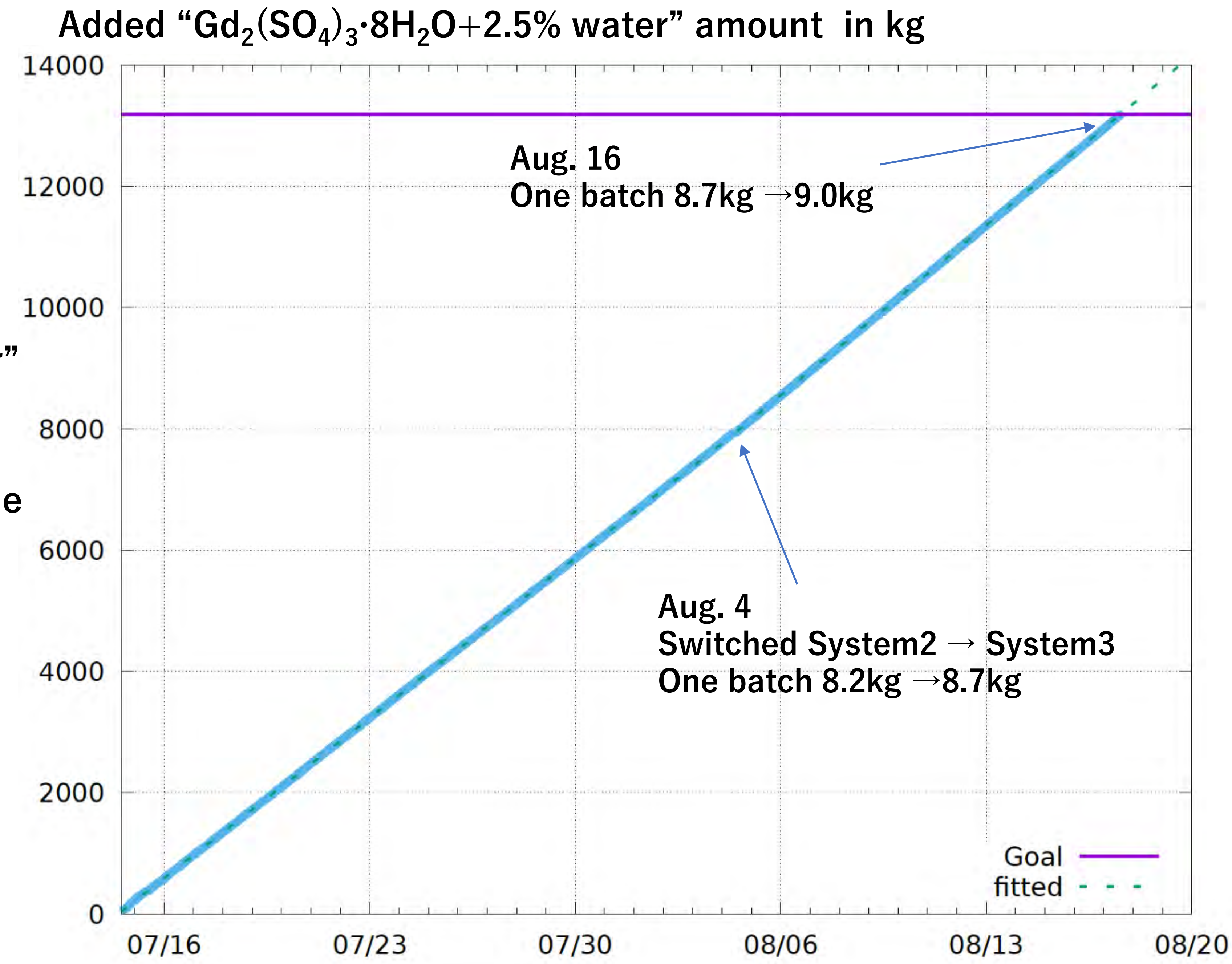
The water in the tank and the water recirculation system =49468000kg

I mean the pure water amount in the system, so 49468000m3. Anyway both 12884./49468000 and 12884./(49468000+12884) give you 0.000260.

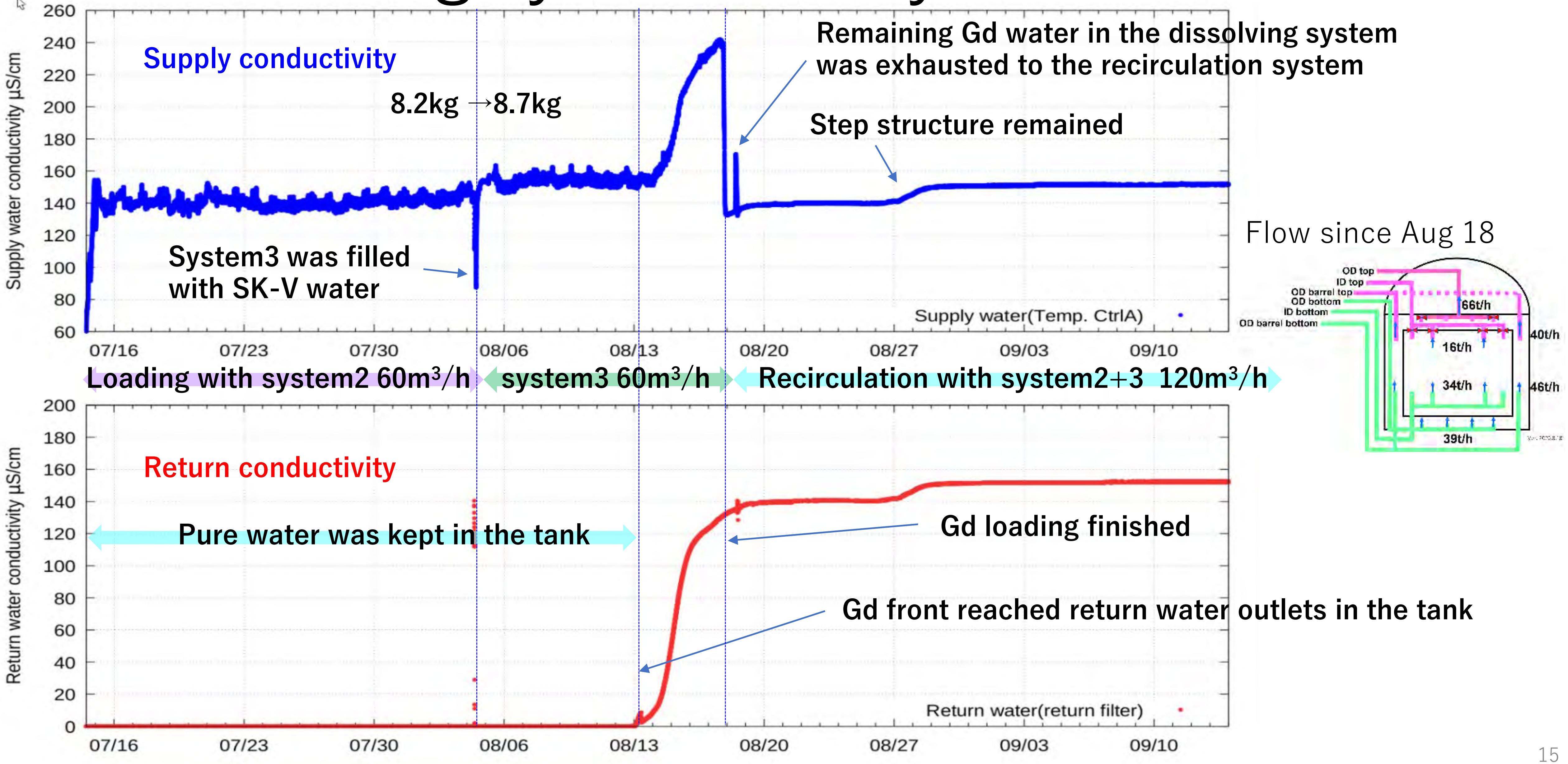
=0.0260% $Gd_2(SO_4)_3 \cdot 8H_2O$

=0.0210% $Gd_2(SO_4)_3$

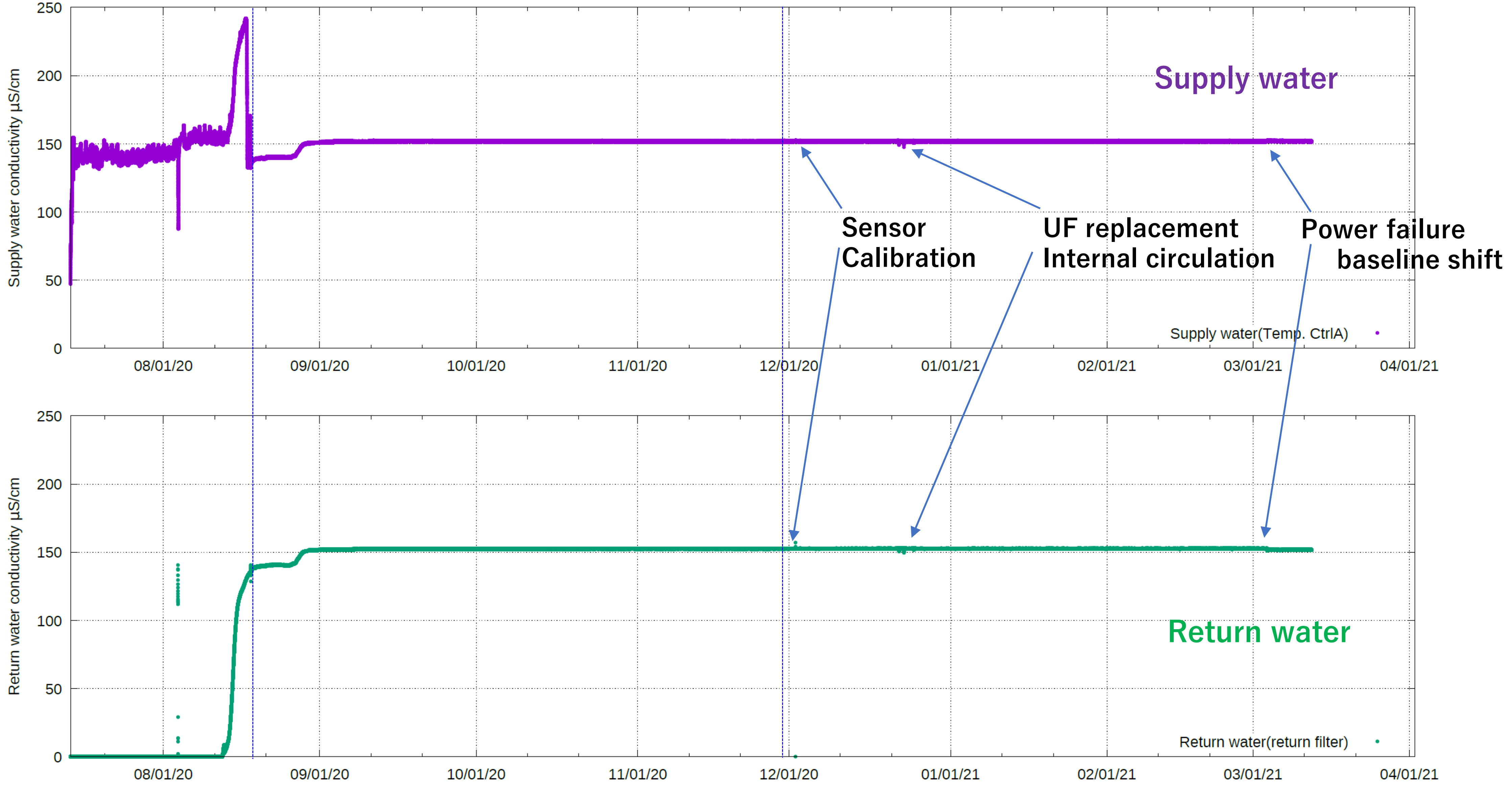
=0.0110% Gd



Gd monitoring by conductivity



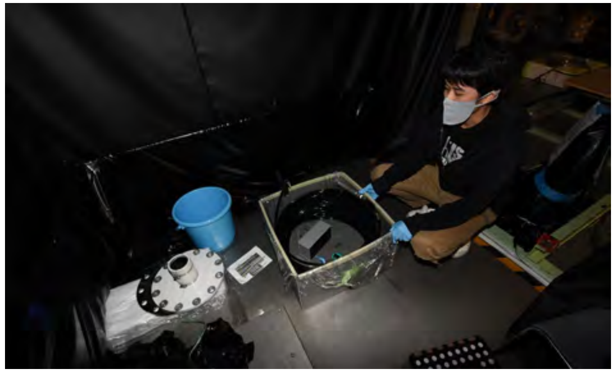
Conductivity suggests stable & uniform Gd concentration



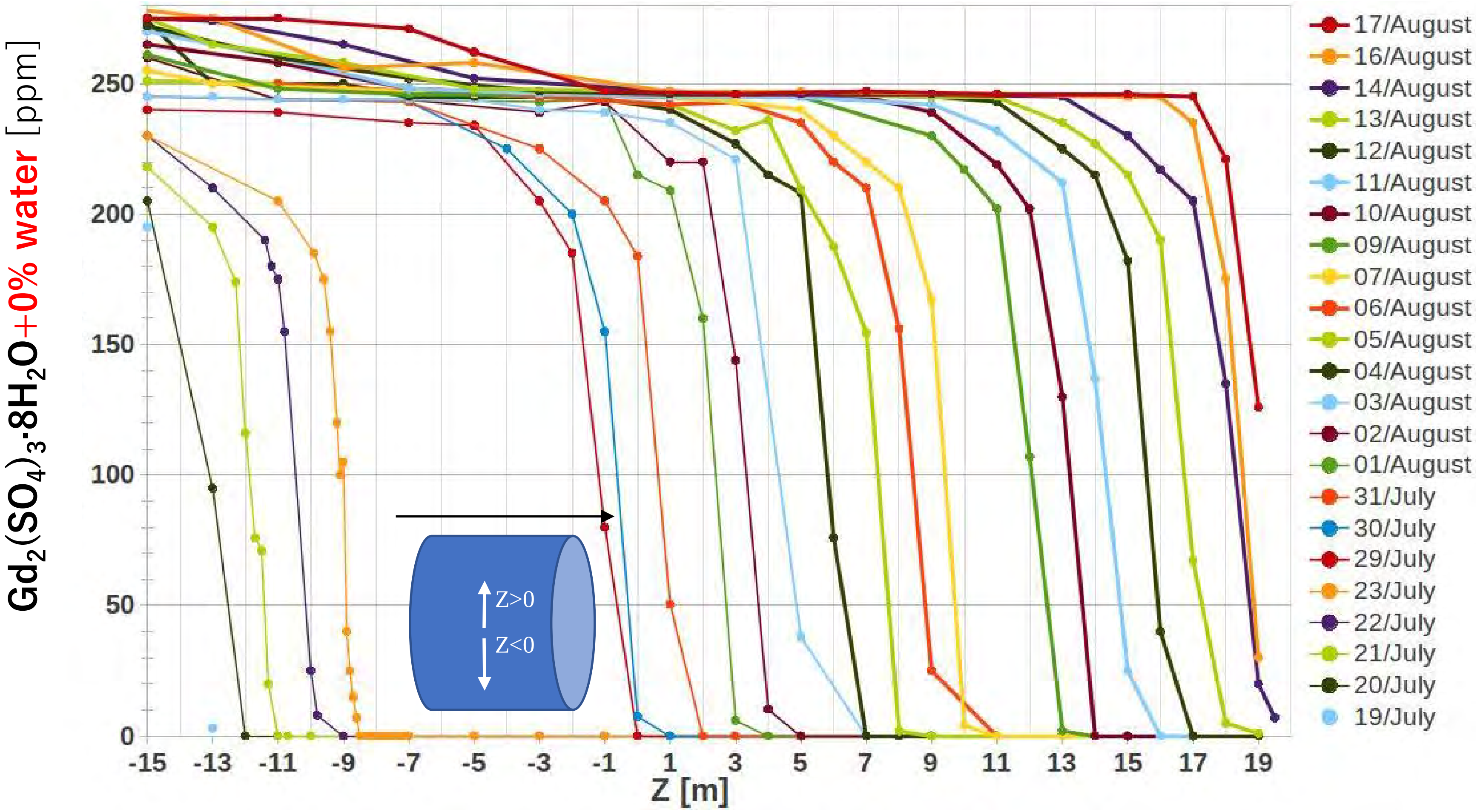
Direct concentration measurement

Atomic Absorption Spectrometer

Ll.Marti



Water sampled directly from various positions in the tank by insertion of tube



Observed the bottom-up flow and the getting uniform Gd condition

Gd concentration and Neutron capture time

Number of captures in Δt

$$\frac{dN_n(t)}{dt}\Delta t \propto -(n_{Gd}\sigma_{Gd}+n_p\sigma_p)v_n \Delta t\, N_n(t)$$

$N_n(t)$ **: number of neutron**

v_n **: neutron velocity**

$n_{Gd}\, n_p$ **: number of nuclei in unit volume**

$\sigma_{Gd}\ \sigma_p$**: capture cross section of Gd**

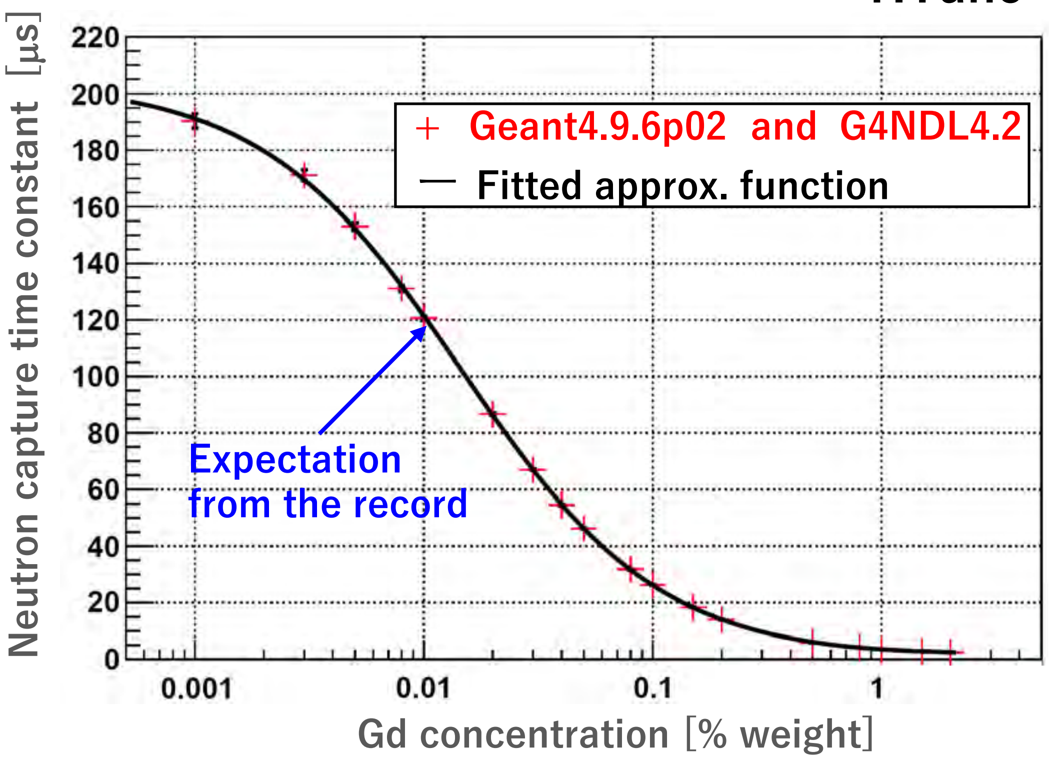
Once neutrons are thermalized, v_n becomes ~ constant

$$N_n(t) \propto exp(-(n_{Gd}\sigma_{Gd}+n_p\sigma_p)\ t)$$

$$\tau \propto \frac{1}{n_{Gd}\sigma_{Gd}+n_p\sigma_p}$$

Gd concentration

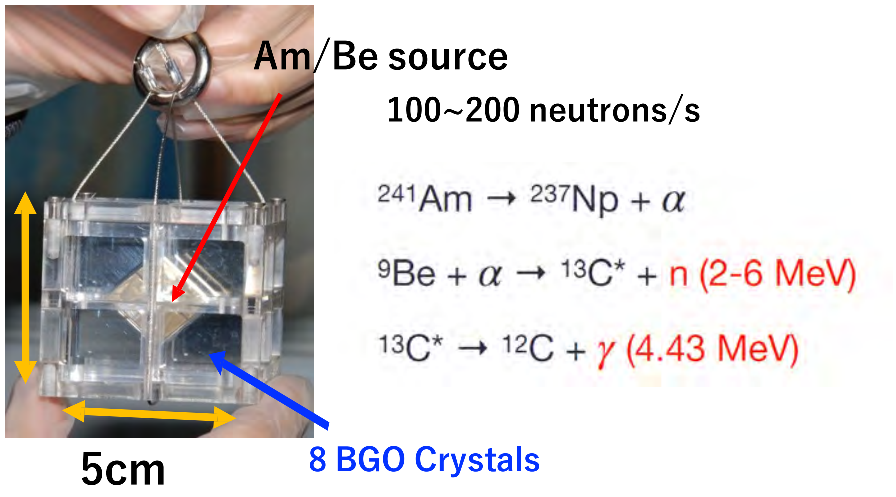
T.Yano



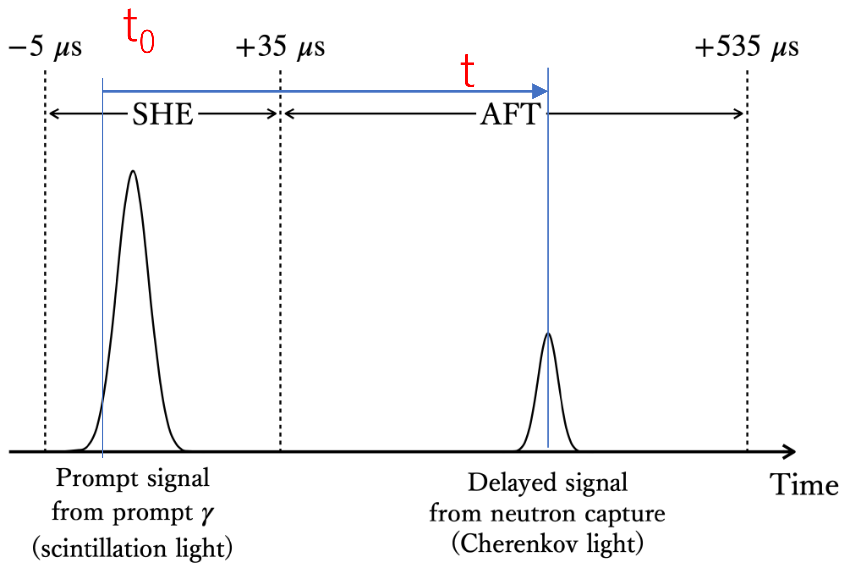
Approx. function

$$c_{Gd} \simeq \left(\frac{8.19}{\tau\,[\mu s]} - 0.0371\right) \times \frac{1}{310} \times 100\ [\%]$$

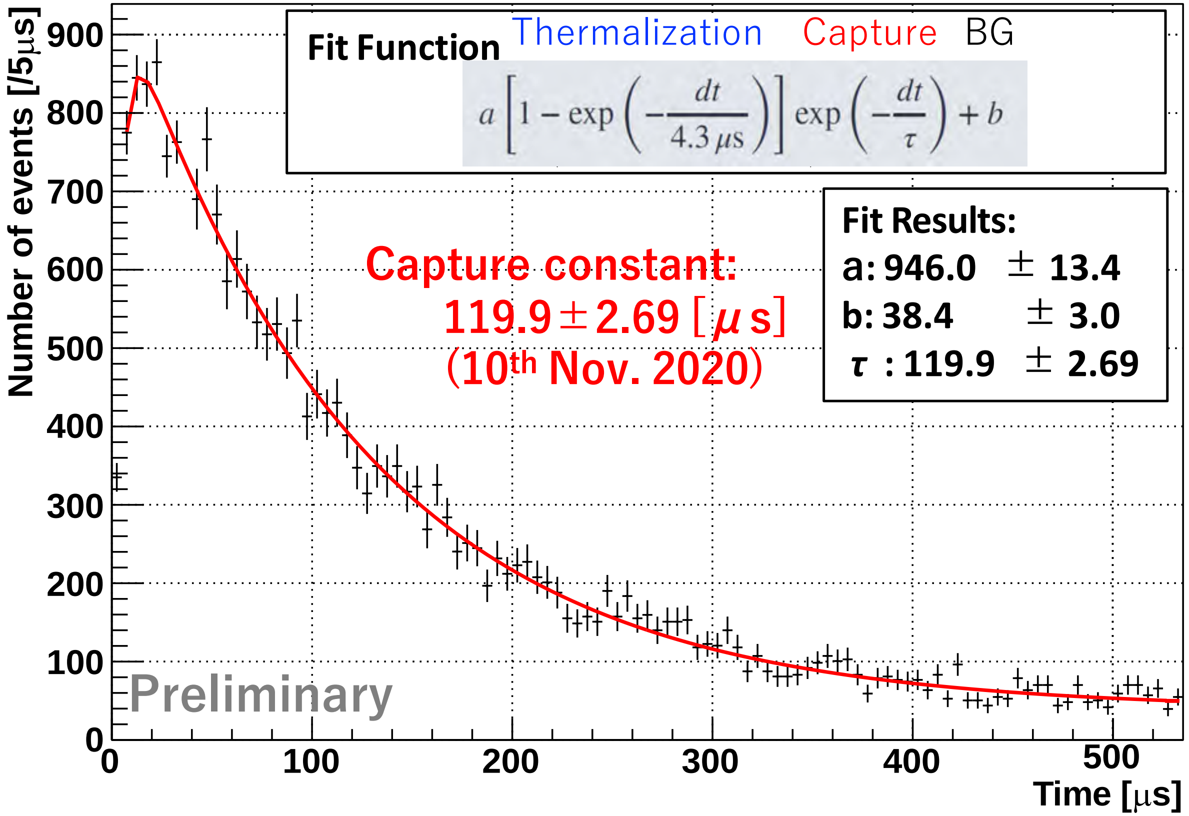
Am/Be + BGO neutron source



- The trigger is the scintillation of 4.4 MeV γ emitted from the Am/Be source simultaneously with the neutrons in the BGO crystal. (SHE trigger threshold 64 hits in 200ns).
- All the PMT hits from -5 to 535 μs before and after the trigger are stored and searched for neutron signals. (sub trigger threshold 30 hits)



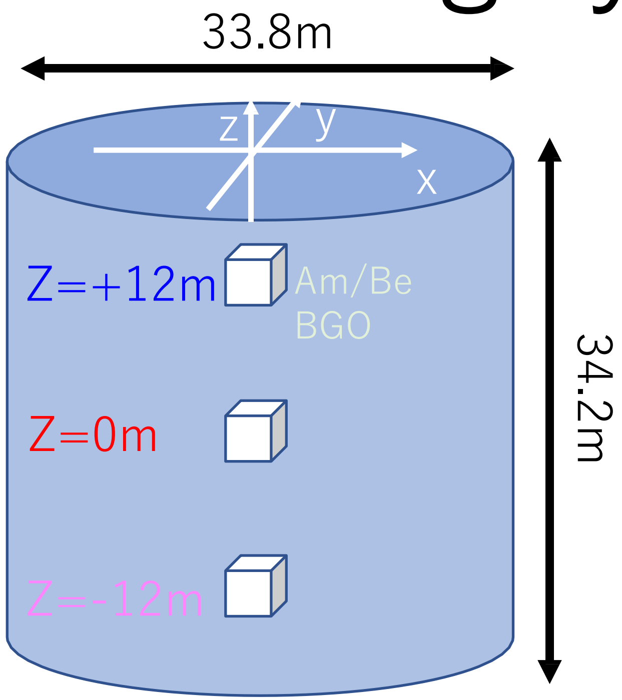
T.Yano

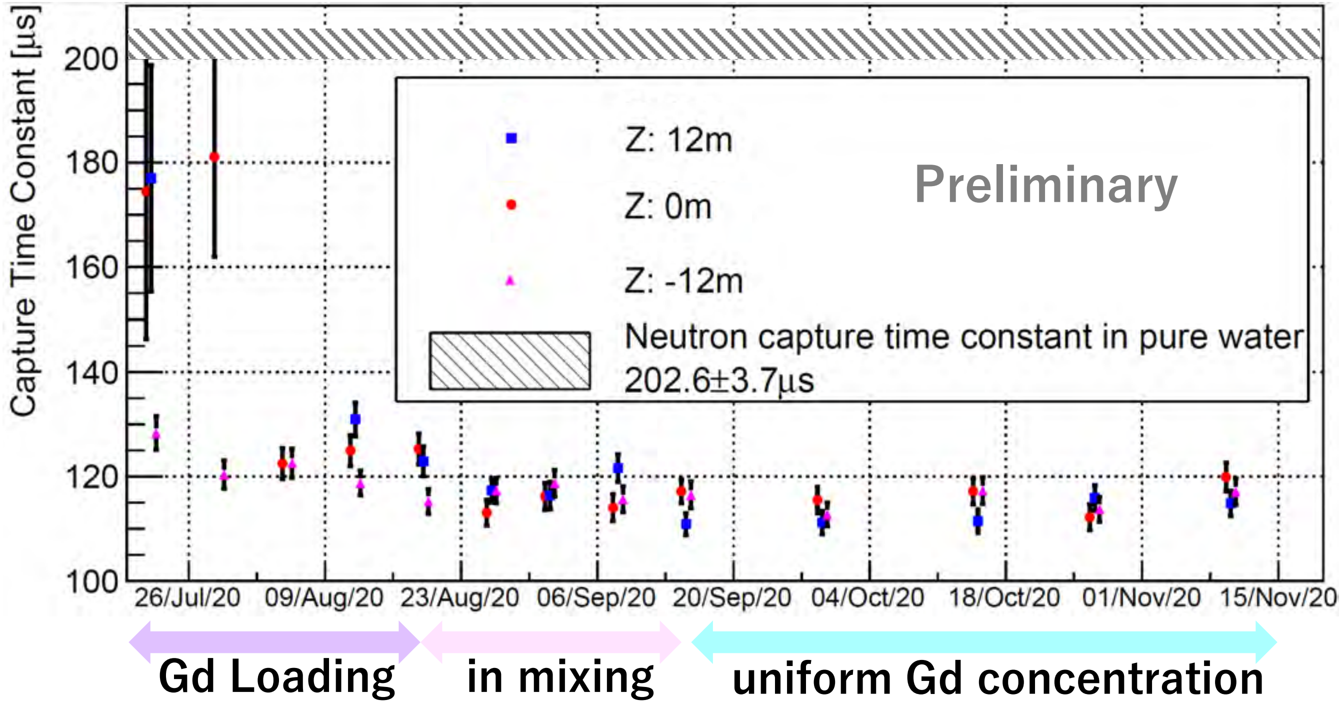


Gd monitoring by Am/Be

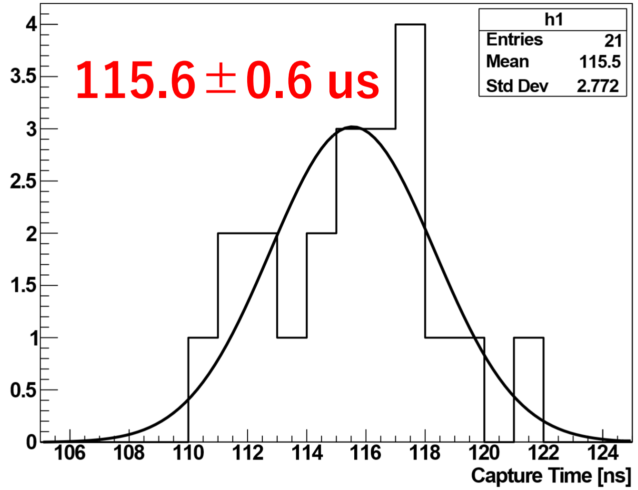
every 2 weeks

T.Yano





After September
all Z positions



Derived Gd concentration
109.1±1.2 ppm

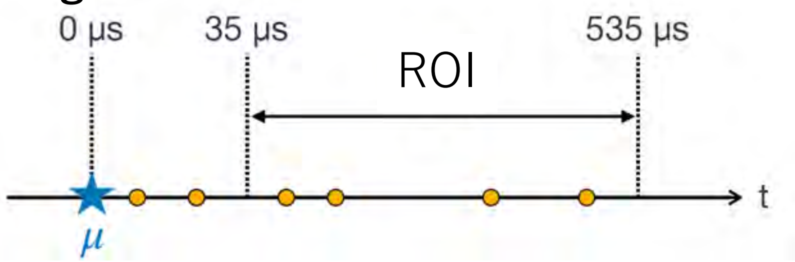
consistent with the record

Spallation neutron by muon

- **Event selection**

M.Shinoki

Timing selection



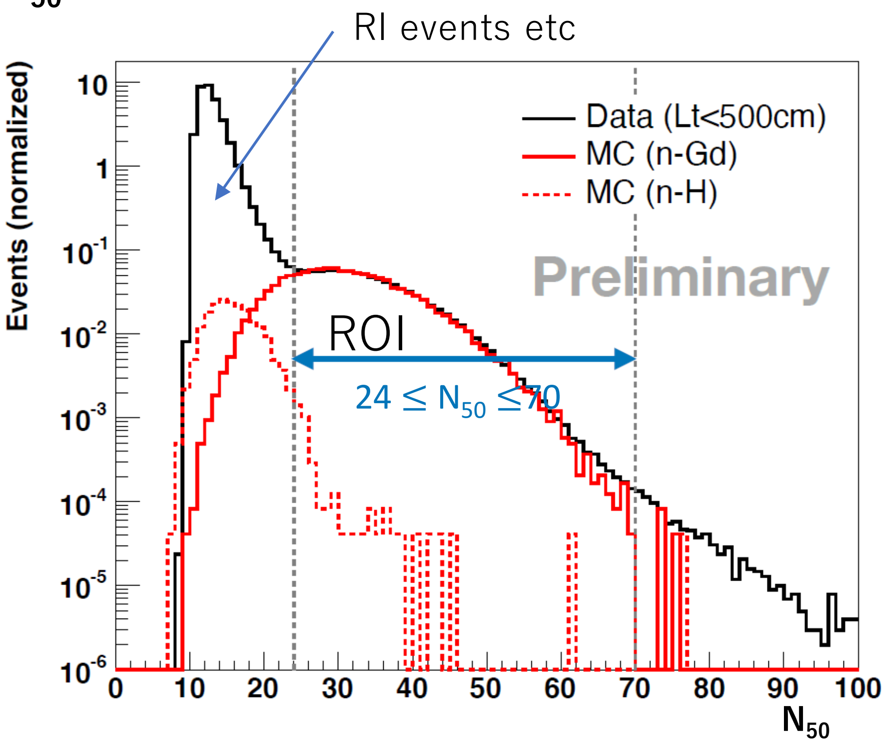
- Michel decay-e ~2.2μs
- Neutron thermalization ~4.3μs
- PMT after pulses 10~20μs

List of spallation products

Isotope	Half-life (s)	Decay mode	Yield (total) ($\times10^{-7}\mu^{-1}g^{-1}cm^2$)	Yield (E > 3.5 MeV) ($\times10^{-7}\mu^{-1}g^{-1}cm^2$)	Primary process
n			2030		
^{18}N	0.624	β^-	0.02	0.01	$^{18}O(n,p)$
^{17}N	4.173	$\beta^- n$	0.59	0.02	$^{18}O(n,n+p)$
^{16}N	7.13	$\beta^-\gamma$ (66%), β^- (28%)	18	18	(n,p)
^{16}C	0.747	$\beta^- n$	0.02	0.003	$(\pi^-,n+p)$
^{15}C	2.449	$\beta^-\gamma$ (63%), β^- (37%)	0.82	0.28	(n,2p)
^{14}B	0.0138	$\beta^-\gamma$	0.02	0.02	(n,3p)
^{13}O	0.0086	β^+	0.26	0.24	$(\mu^-,p+2n+\mu^-+\pi^-)$
^{13}B	0.0174	β^-	1.9	1.6	$(\pi^-,2p+n)$
^{12}N	0.0110	β^+	1.3	1.1	$(\pi^+,2p+2n)$
^{12}B	0.0202	β^-	12	9.8	$(n,\alpha+p)$
^{12}Be	0.0236	β^-	0.10	0.08	$(\pi^-,\alpha+p+n)$
^{11}Be	13.8	β^- (55%), $\beta^-\gamma$ (31%)	0.81	0.54	$(n,\alpha+2p)$
^{11}Li	0.0085	$\beta^- n$	0.01	0.01	$(\pi^+,5p+\pi^++\pi^0)$
^{9}C	0.127	β^+	0.89	0.69	$(n,\alpha+4n)$
^{9}Li	0.178	$\beta^- n$ (51%), β^- (49%)	1.9	1.5	$(\pi^-,\alpha+2p+n)$
^{8}B	0.77	β^+	5.8	5.0	$(\pi^+,\alpha+2p+2n)$
^{8}Li	0.838	β^-	13	11	$(\pi^-,\alpha+{}^2H+p+n)$
^{8}He	0.119	$\beta^-\gamma$ (84%), $\beta^- n$ (16%)	0.23	0.16	$(\pi^-,{}^3H+4p+n)$
^{15}O			351		(γ,n)
^{15}N			773		(γ,p)
^{14}O			13		(n,3n)
^{14}N			295		$(\gamma,n+p)$
^{14}C			64		(n,n+2p)
^{13}N			19		$(\gamma,{}^3H)$
^{13}C			225		$(n,{}^2H+p+n)$
^{12}C			792		(γ,α)
^{11}C			105		$(n,\alpha+2n)$
^{11}B			174		$(n,\alpha+p+n)$
^{10}C			7.6		$(n,\alpha+3n)$
^{10}B			77		$(n,\alpha+p+2n)$
^{10}Be			24		$(n,\alpha+2p+n)$
^{9}Be			38		$(n,2\alpha)$
sum			3015	50	

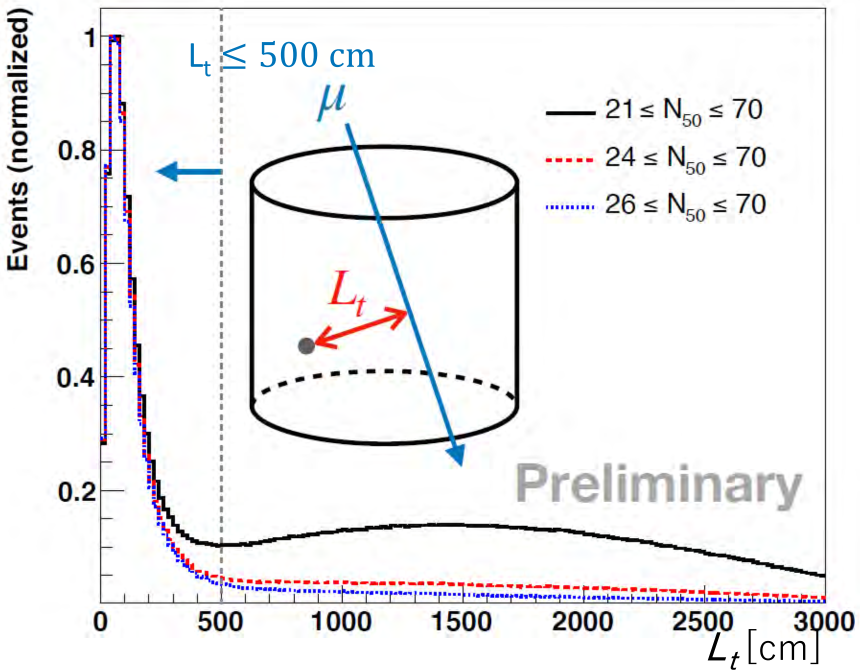
S.Li and J.Beacom, Phys. Rev. C 89, 045801 (2014)

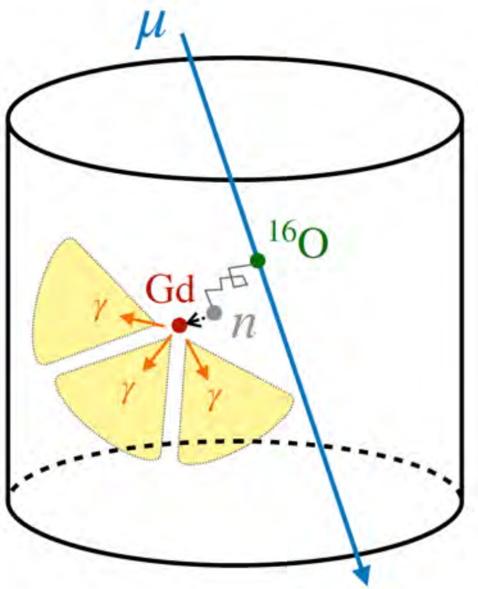
N_{50} selection



Distance to μ track selection

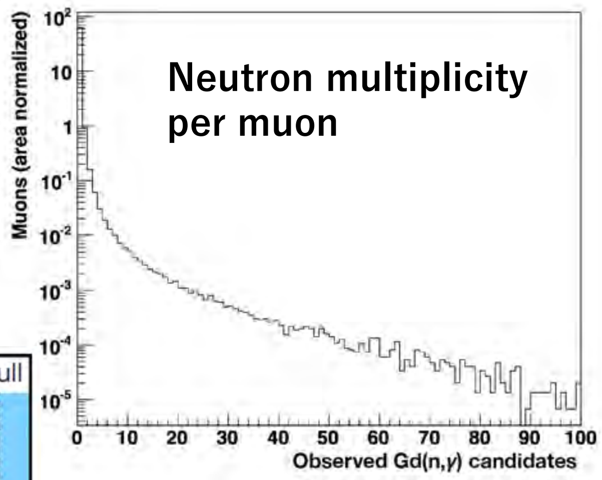
Neutron capture occurs near the muon track

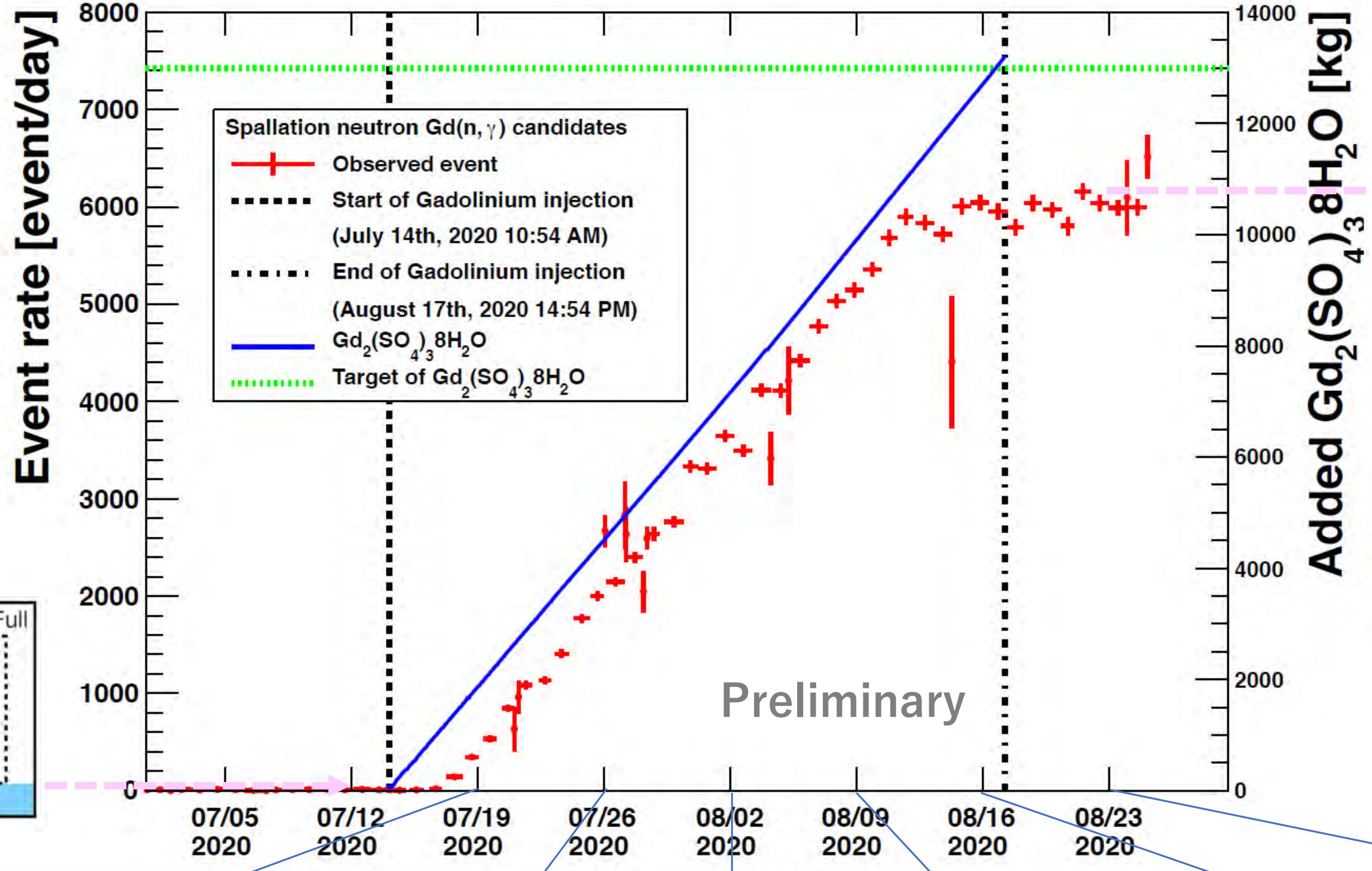


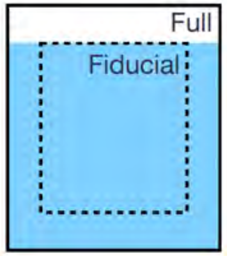


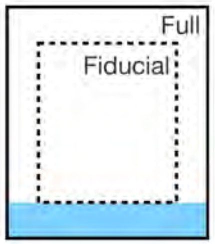
M.Shinoki

Neutron event rates vs. Gd-loading





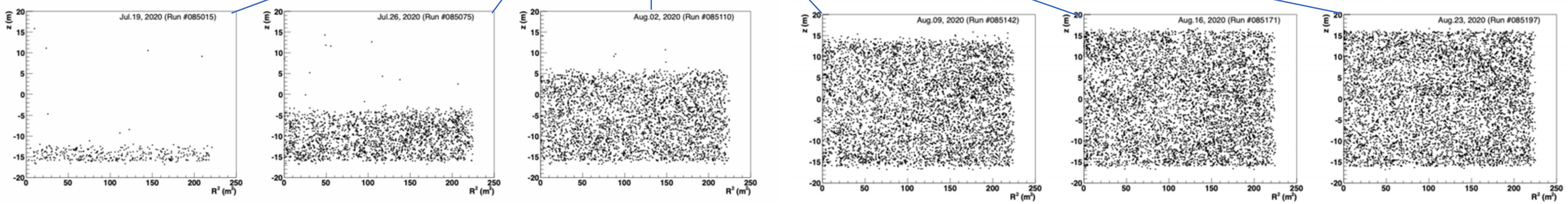




Neutron yields in water is under calculation

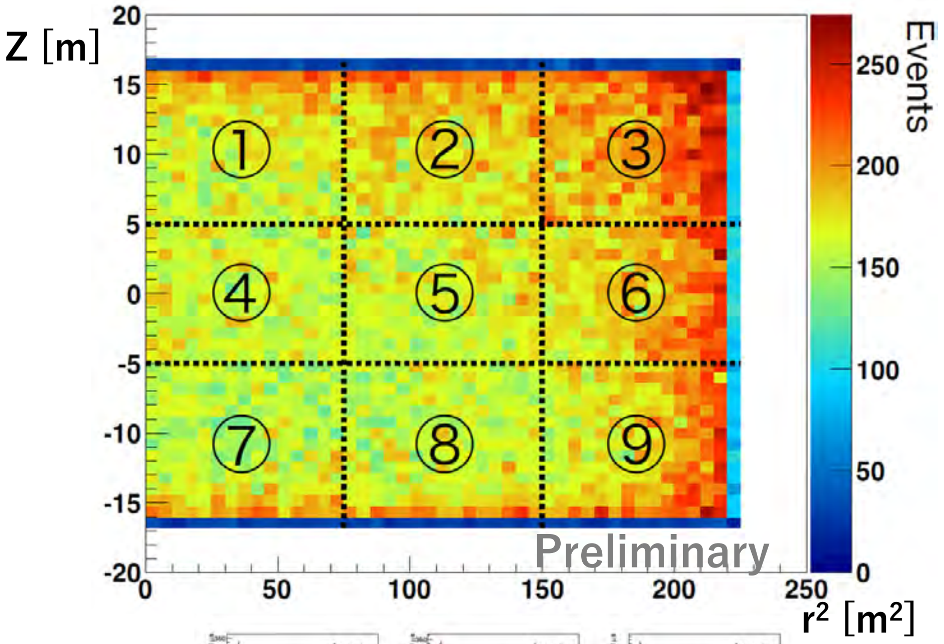
$$Y_n = \frac{N_n}{N_\mu \, L_\mu \, \rho \, V_{corr}}$$

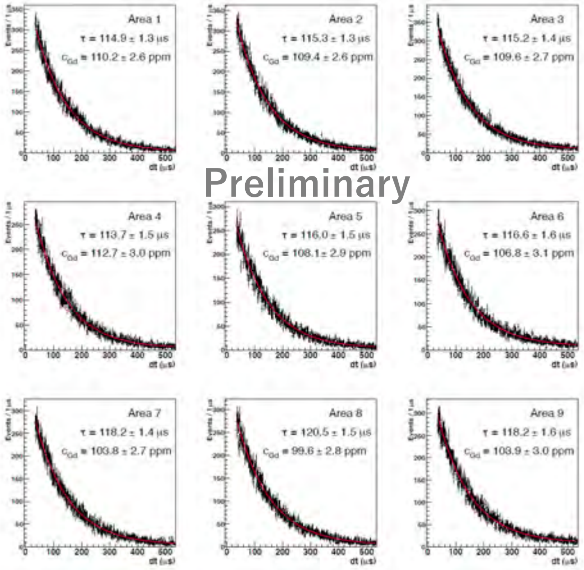
- N_n : The number of neutrons produced by cosmic-ray muons
- N_μ : The number of selected muons
- L_μ : The average path length of muons
- ρ : The density of Gd water
- V_{corr} : Fiducial volume / Full volume

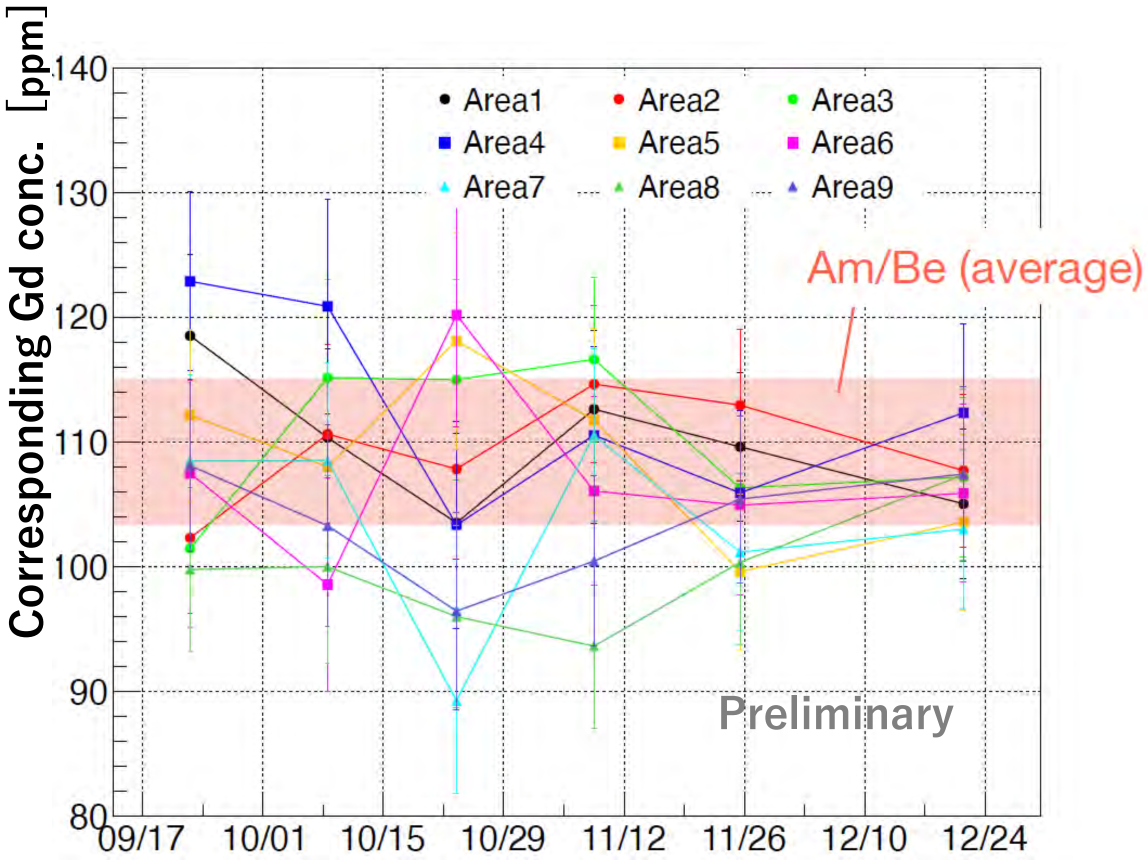


Gd monitoring by spallation neutron

M.Shinoki



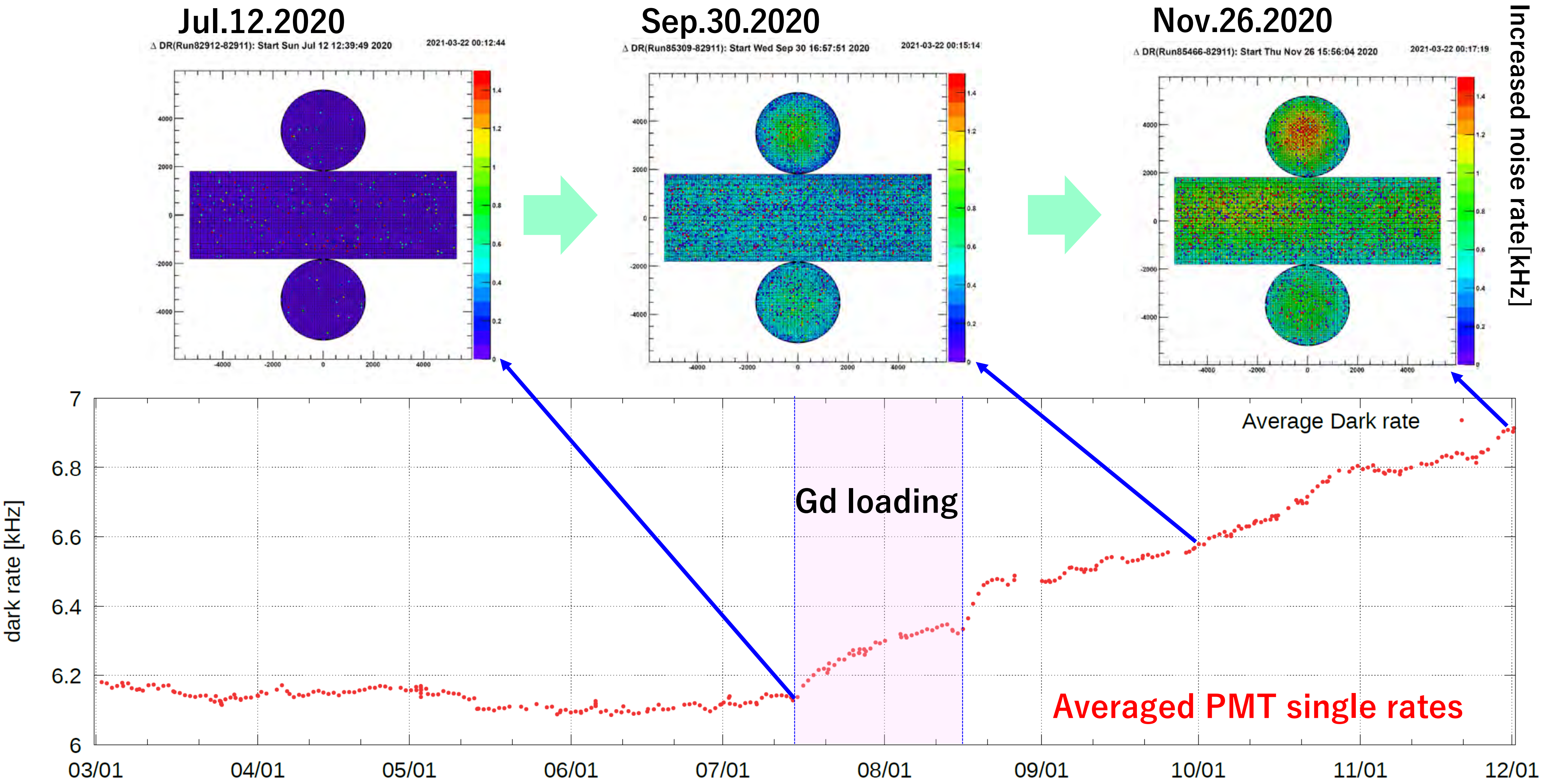




The position dependence has been decreased.

The Gd concentration has become uniform throughout the tank.

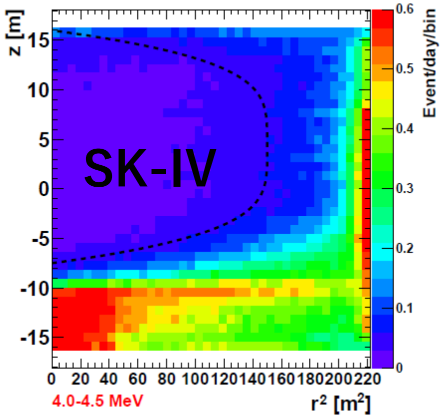
Dark noise issue

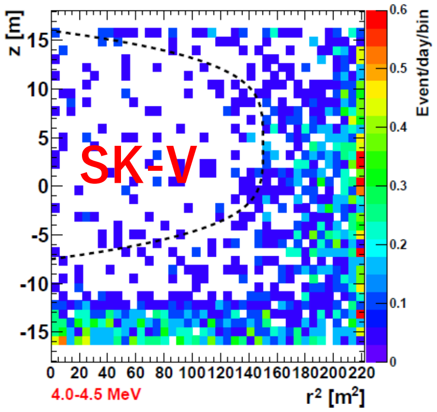


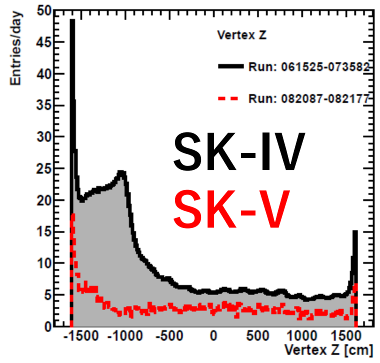
Water flow change

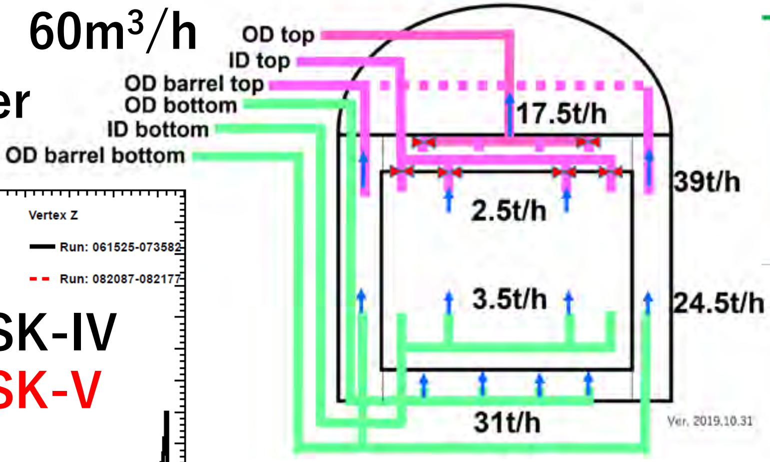
SK-V configuration was valid only for 60m3/h flow
For 120m3/h the pipe modification was needed in Feb. 2020

SK-V: intentional stagnation → Lowest Rn ever

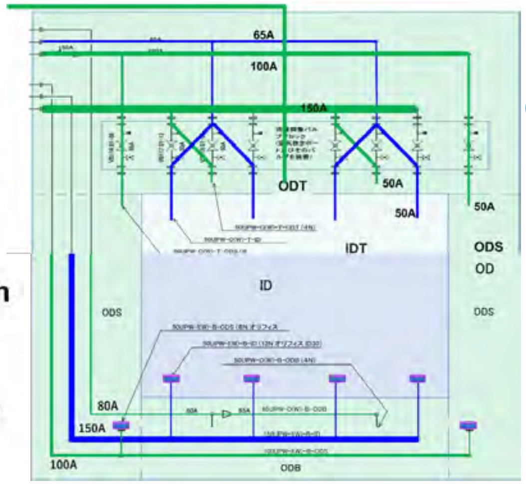






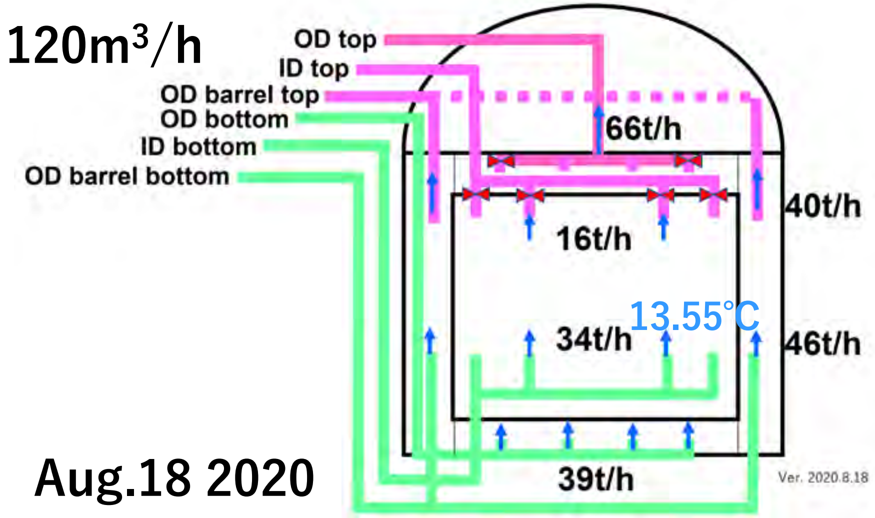


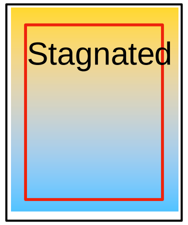
SK-V flow: minimum ID flow



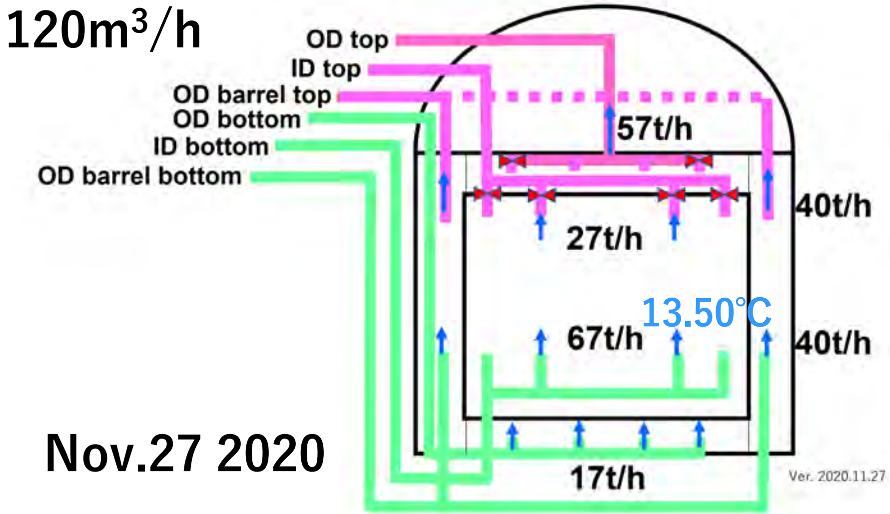
Small OD pipe installed in 2018

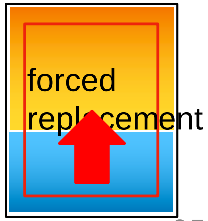
Minimum ID water flow was set initially in SK-VI





Increased ID flow and lowered supply temperature





Tracing the flow by Rn injections

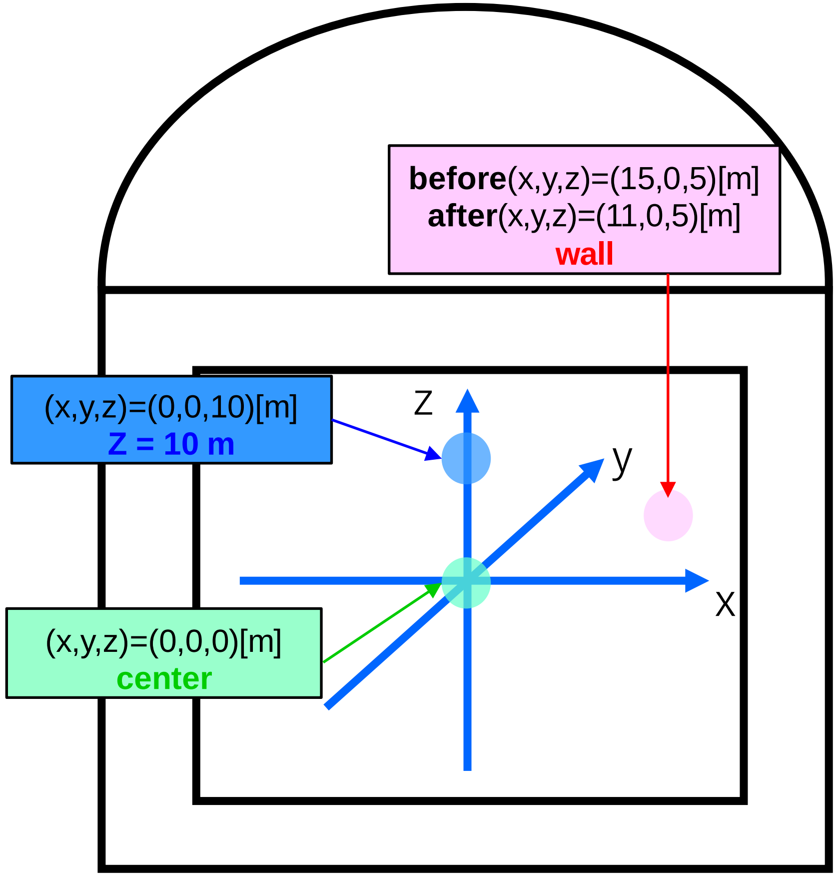
Y.Kanemura

- **Rn injection before and after the flow change**

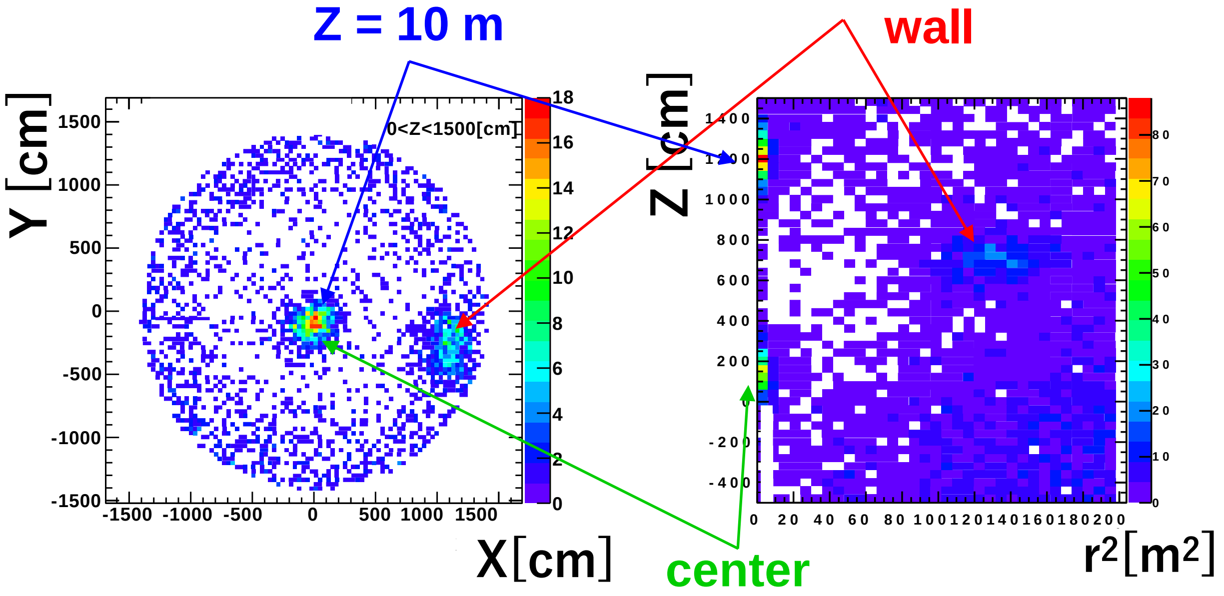
2020.11.7 : 1st Rn injection
2020.11.27: Change the water flow
2020.12.8: 2nd Rn injection

Injected Rn concentration (Independently measured)

1st Injection:	**center** → ~8 Bq/L	**2nd injection:**	**center** → 6.2±0.2 Bq/L
	wall → ~8 Bq/L		**wall** → 6.0±0.2 Bq/L
	Z=10 m → ~8 Bq/L		**Z=10 m** → 4.7±0.2 Bq/L



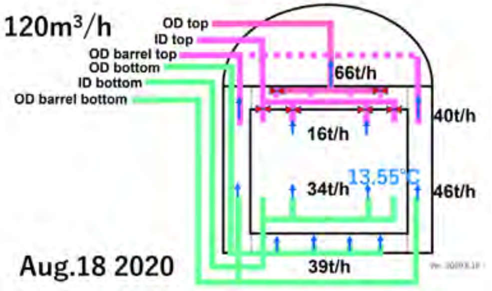
ex) 2nd Injection

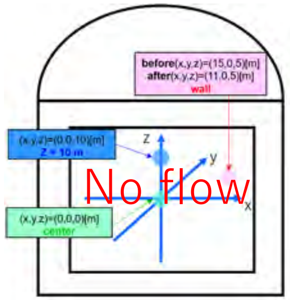


Flow in Z direction

Y.Kanemura

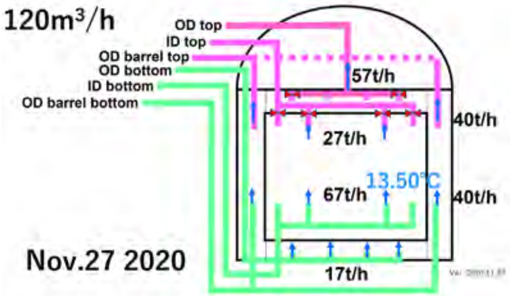
Before

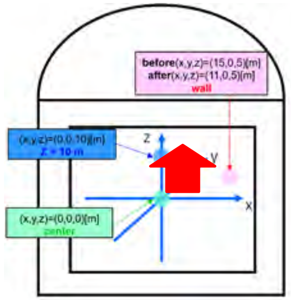




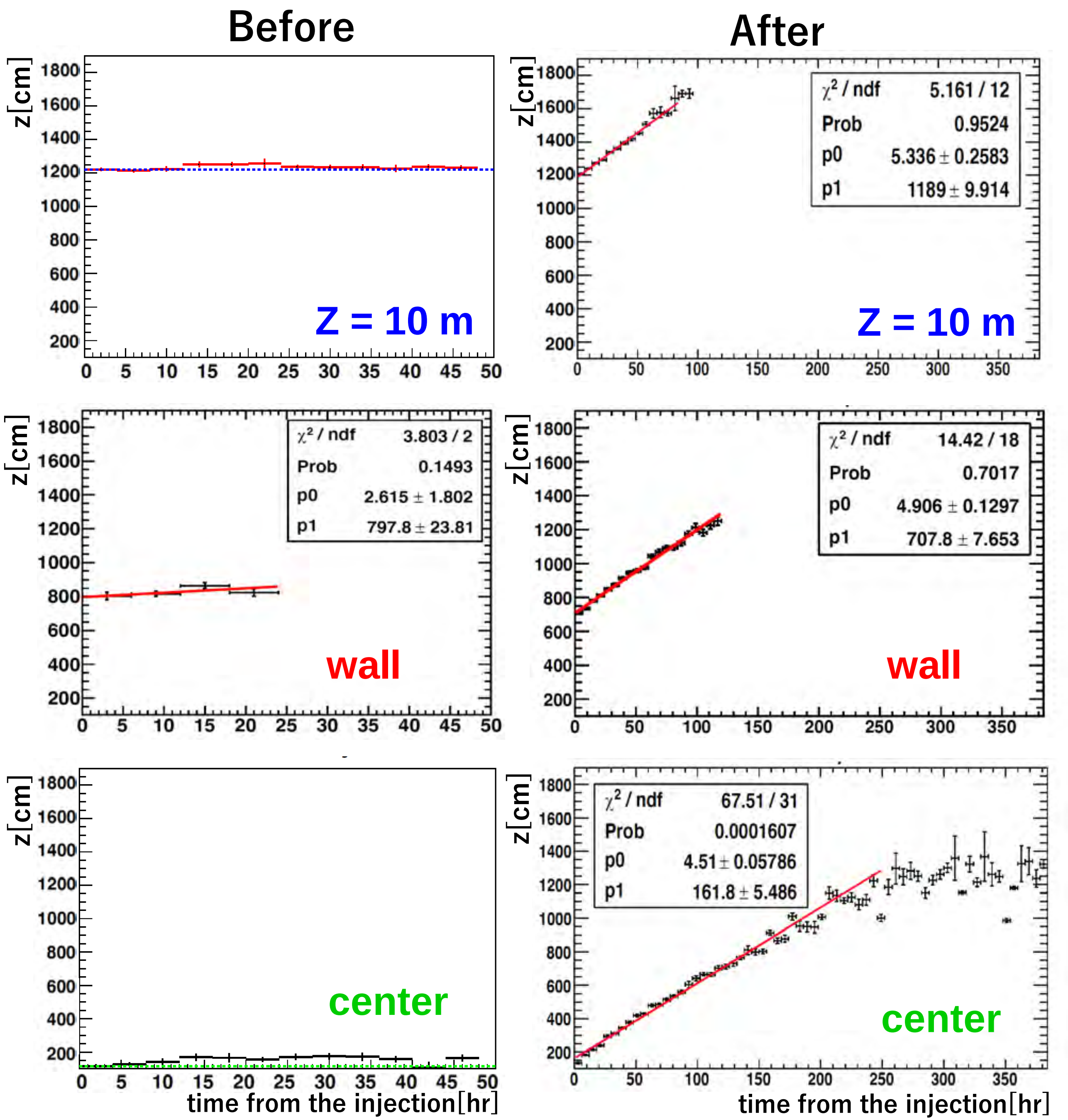
There was little water flowing → stagnation

After



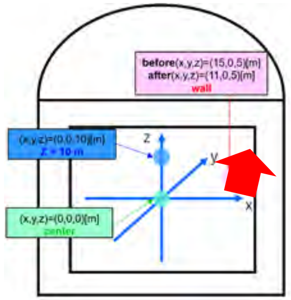


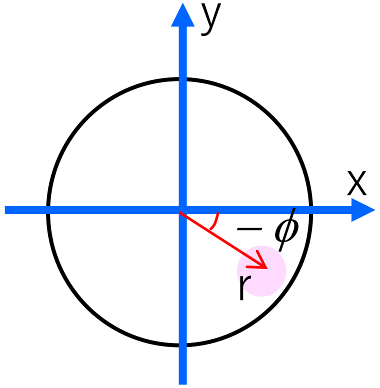
The water is rising at 5 cm/hr for all Z>0
After 250hr, it stagnates again as the temperature difference between the supply water and the tank water became small again.



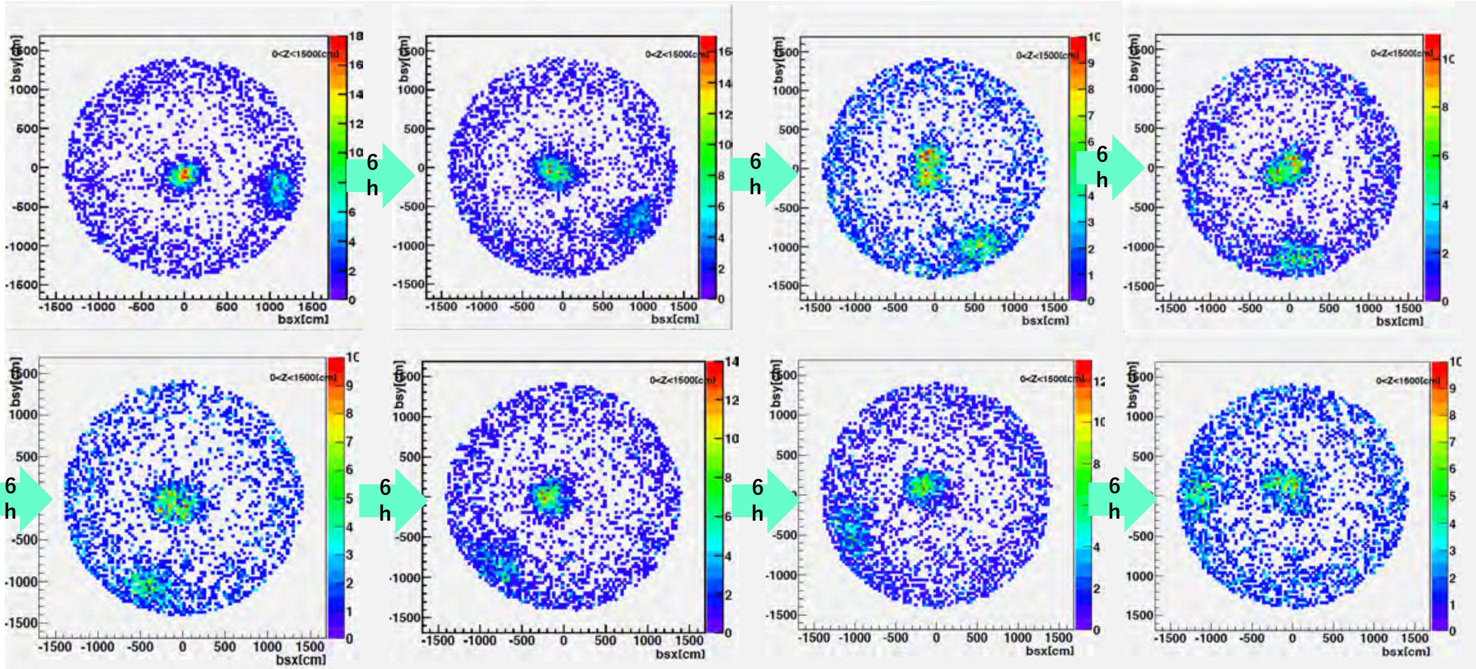
Flow in r and ϕ direction

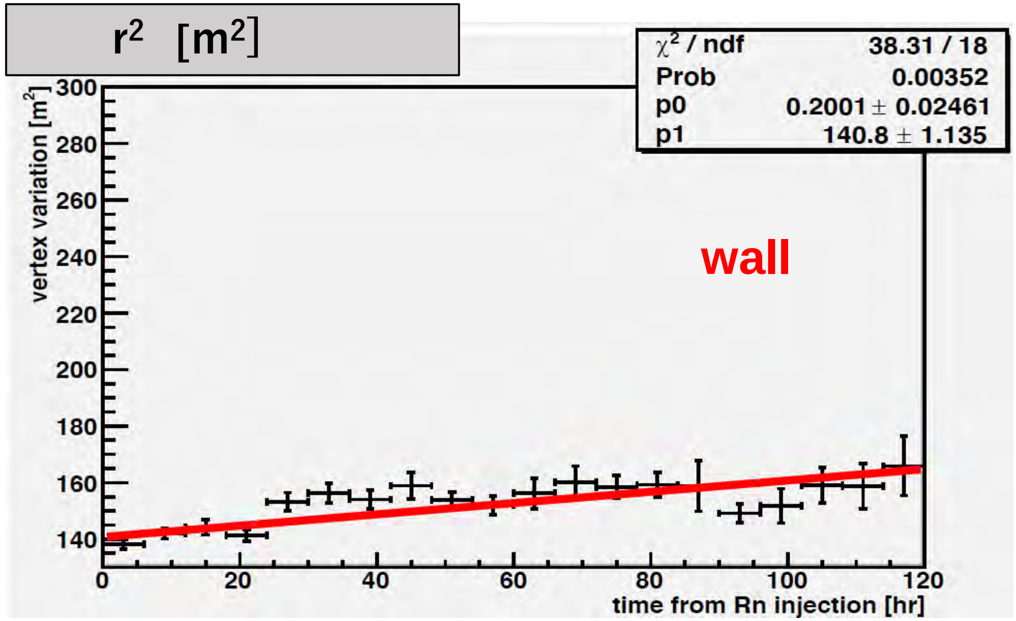
After

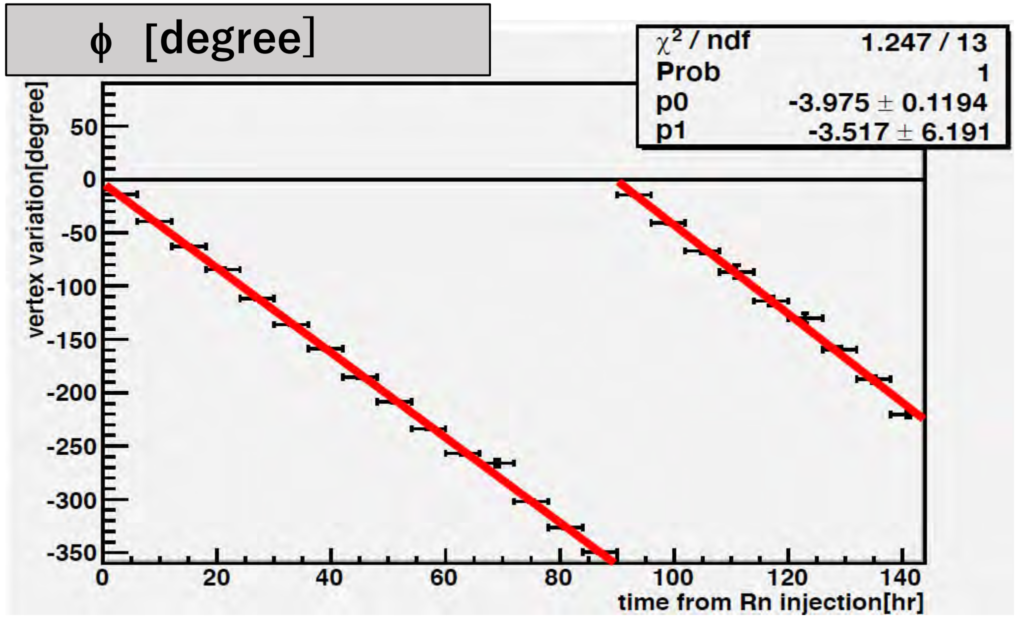




Y.Kanemura

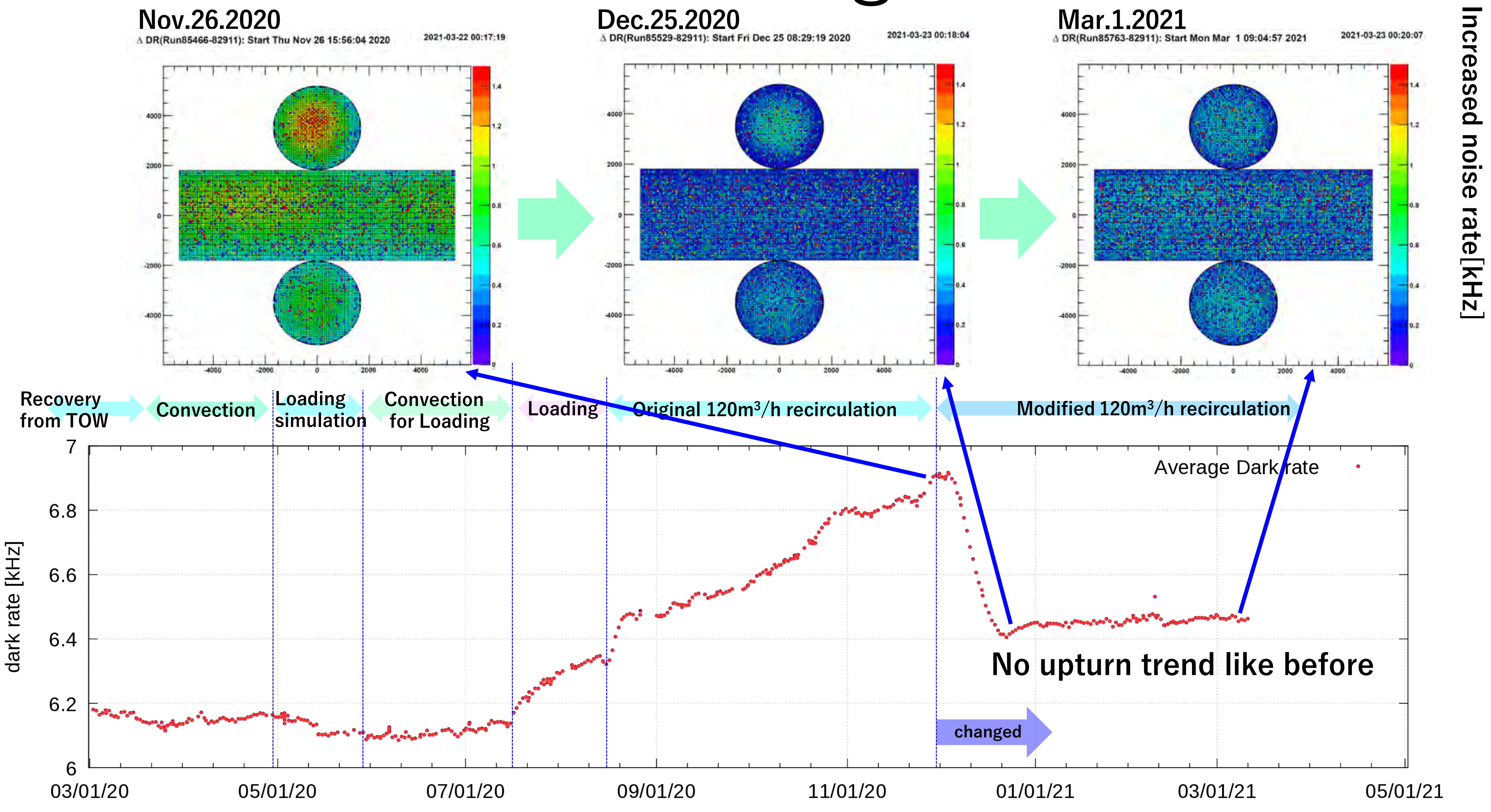




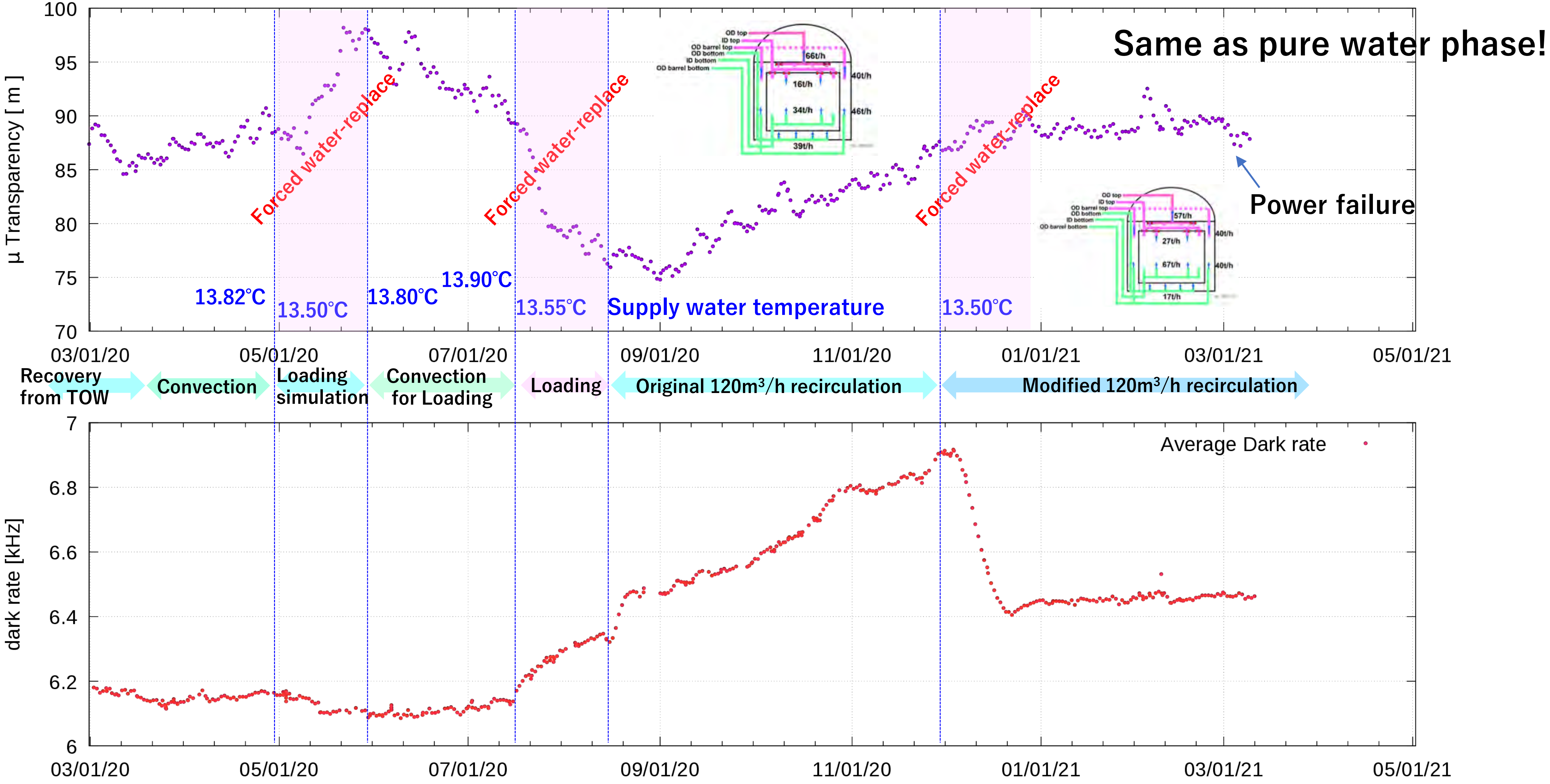


r:Moving toward the SK wall at a speed of 0.83±0.10 [cm/hr]
ϕ:Rotating clockwise at a speed of 4.0 [° /hr].

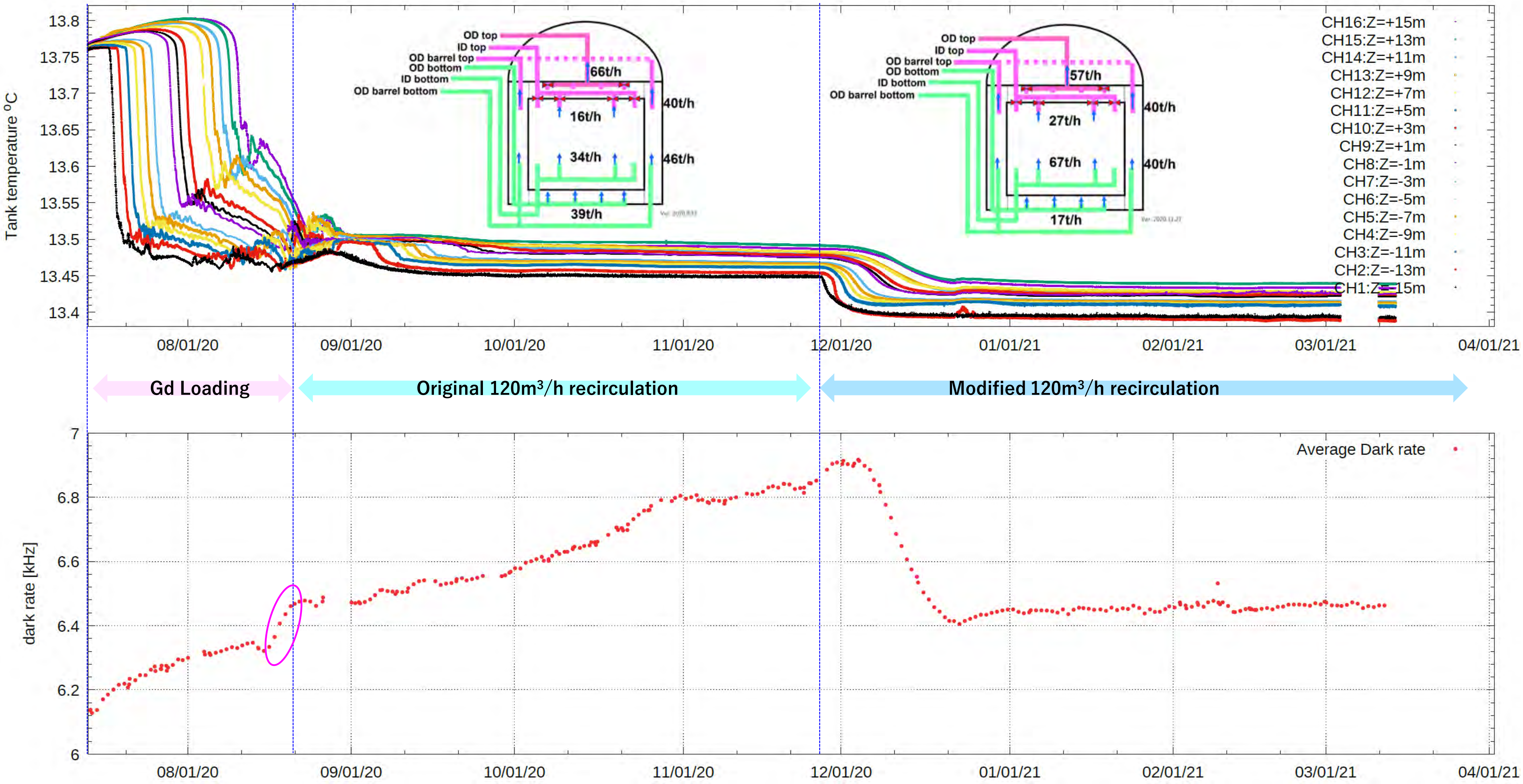
The results of the flow change



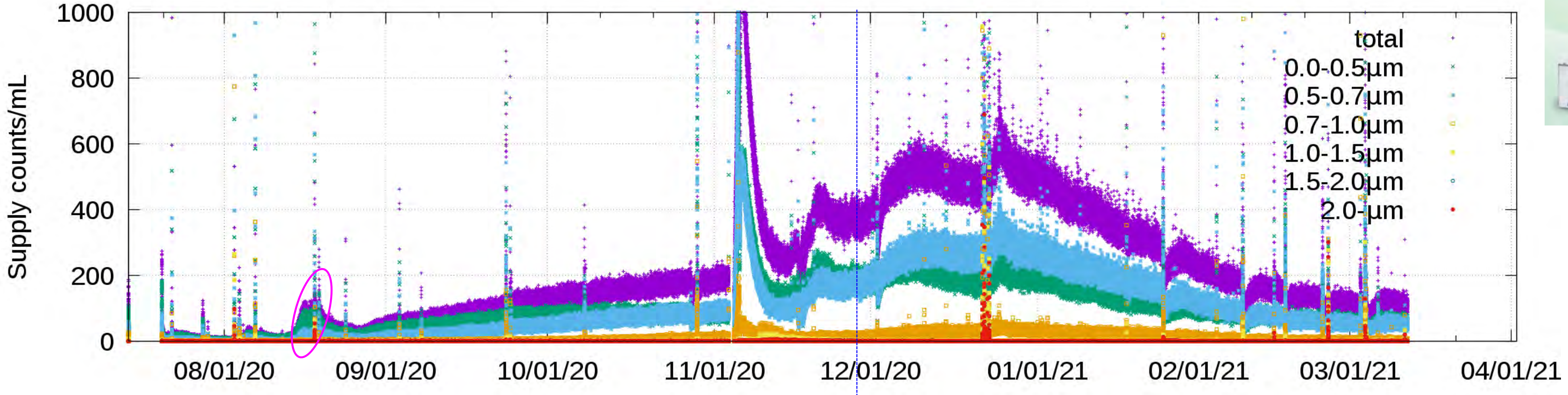
Transparency and dark rate in the past 1year



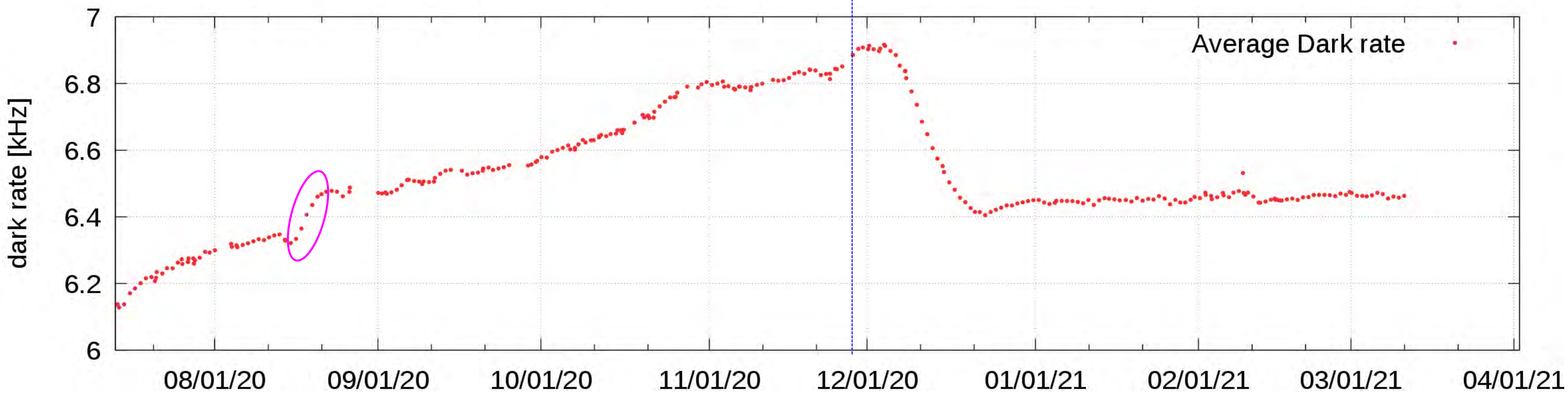
Temperature and dark rate in SK-VI



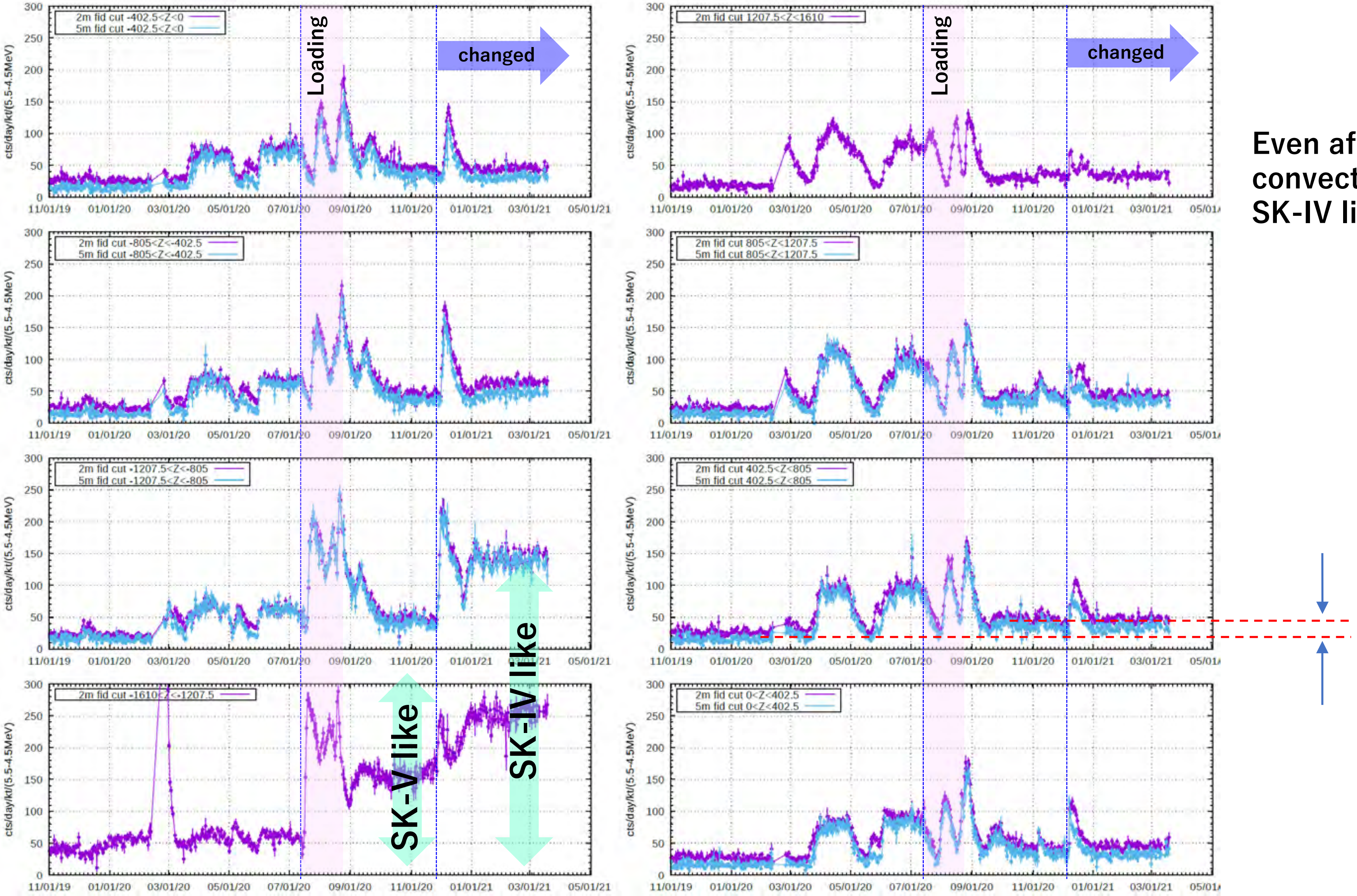
Bacteria and dark rate in SK-VI



RION XL-10B



Flow change effect on the convection/Rn

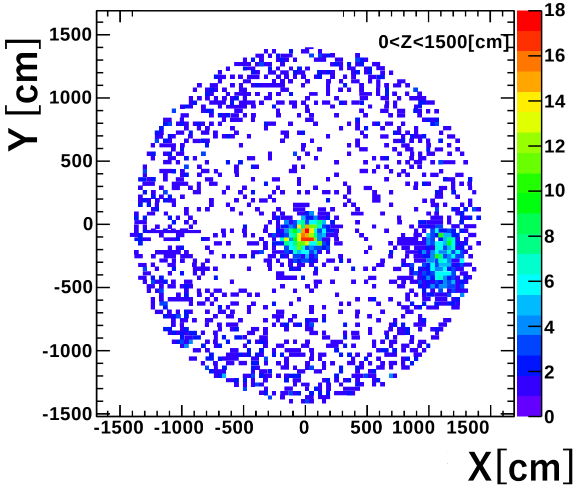


Even after the change,
convection region is kept Z< -11m
SK-IV like flow is realized

This is the issue!
^{222}Rn? ^{228}Ra? ^{226}Ra? from Gd?

Estimation from the Rn Injection

Y.Kanemura

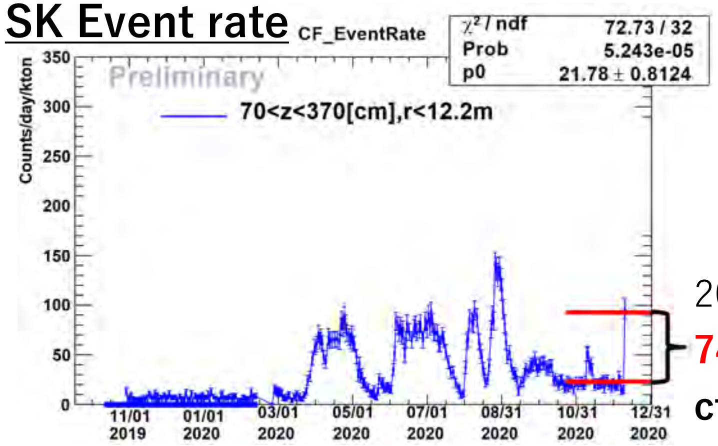


Injected Rn concentration

(9.73 ± 0.314) Bq / ($12.2^2 \times \pi \times 3$) m^3
= **6.94 ± 0.22** mBq/m^3

$$\frac{\text{Rn concentration [mBq/m}^3\text{]}}{\text{SK Event rate [cts/day/ktons]}} = (9.25 \pm 0.31) \times 10^{-2}\ \text{(mBq/m3)/(cts/day/ktons)}$$

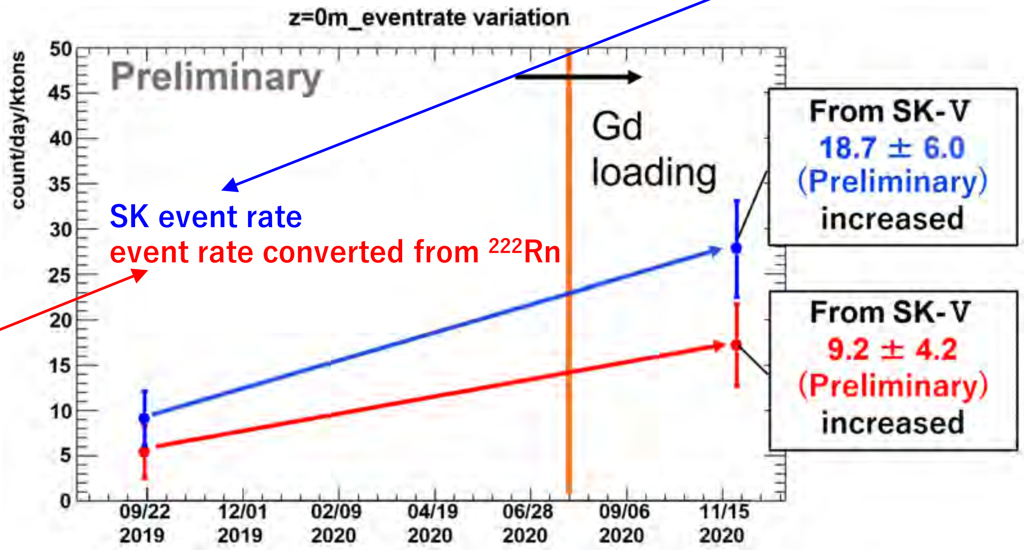
SK Event rate



2020/12/8
74.9
cts/day/ktons

Results of the direct Rn measurement

z=0[cm]	Rn concentration[mBq/m³]
2019/9/19	0.38±0.21
2020/11/24	1.23±0.32



Half of the increase can be explained by ^{222}Rn. As there is no further decay, ^{226}Ra should remain there.

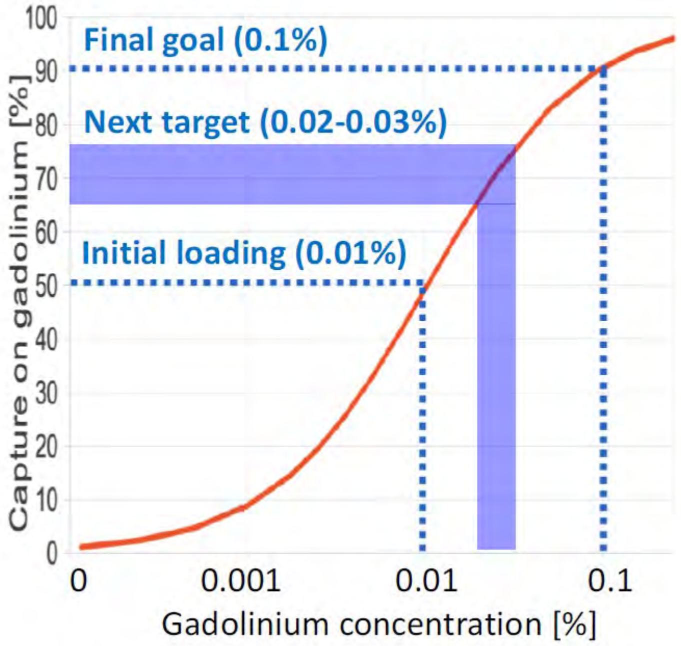
The rest half might be from ^{228}Ra, or mis-reconstruction events of near the wall?

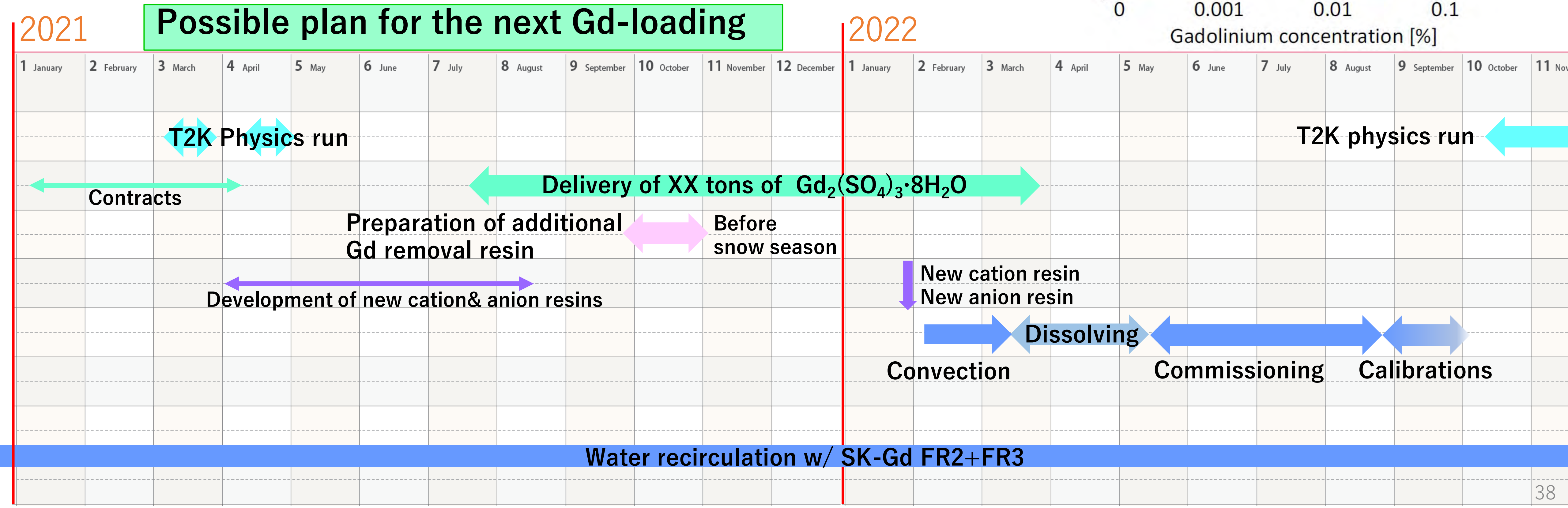
It's larger than that we had expected.→ Other ^{226}Ra source? or Underestimated the effects of RIs?
(Energy scale, resolution and cuts are not tuned yet)

Next step

Planning to dissolve up to ~26 tons of additional $Gd_2(SO_4)_3 \cdot 8H_2O$ in 2021-2022

- Target Gd concentration: 0.02-0.03% (Currently 0.01%)
- Gd capture efficiency: 65-75% (Currently 50%)





まとめ

- 2020年 0.011% Gdを導入し、ついにSK-Gdを開始した
  - DSNBを実際に探索できる感度を有しているはず
- 検出器全体でGdの濃度は一様になっている
  - 直接測定、Am/Be線源、Spallationによる中性子で確認
- 導入後、水が光っているように見える
  - 滞留と相関があり、水を一度”入れ替える”と低減した
  - 原因は調査中
- 低エネルギーBGが予想より多い
  - 228Ra, 226Ra, mis-reconstruction等の可能性を調査中
  - SK-IV程度の太陽ニュートリノ観測は可能
- 2022年 Gd 0.03%を目指している(来年の今頃)
  - 上記問題の対応
  - 原料の酸化ガドリニウムの放射性不純物レベルが高い、Gd価格急上昇中