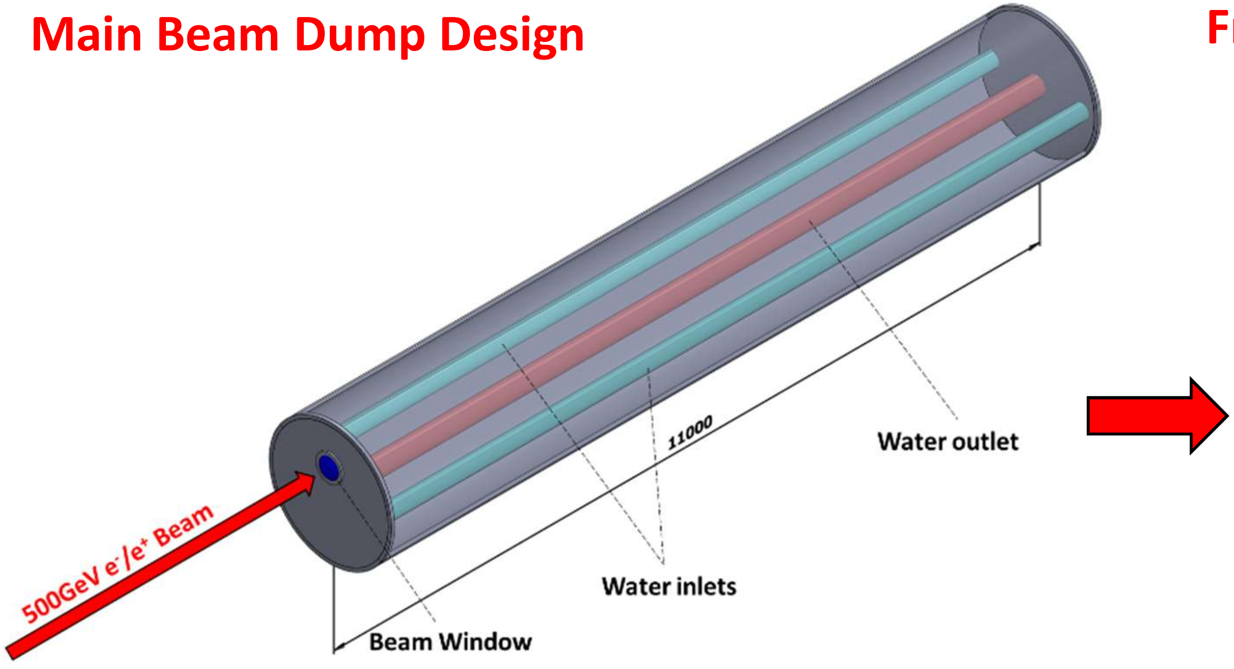
Design check of ILC Main Beam Dump

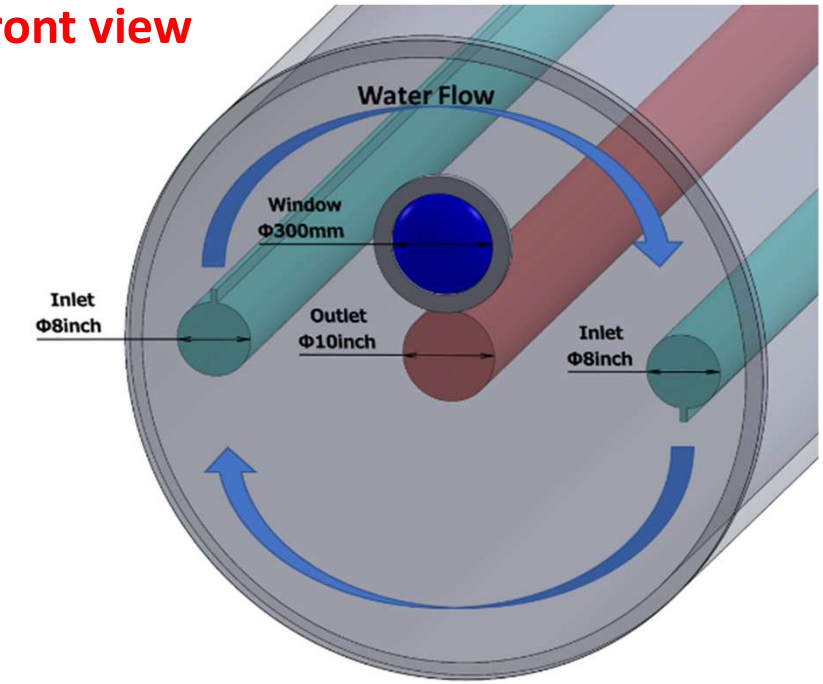
Yu Morikawa

Base design of ILC Main Beam Dump

Main Beam Dump Design



Front view



【Base Design】

- **Water power absorber** and **forced convection** to extract the heat.
  - * Water is compressed **1 MPa** ⇒ **boiling temp 180℃**
  - * Vortex water flow ⇒ Mass flow rate : **104.5kg/s** each inlet, Ave flow velocity **2.17m/s**
- Beam Window made of **Ti-6Al-4V**.

  Beam sweep : 1kHz sweep, sweep radius : **6cm**

What are required conditions in 250GeV operation?

ILC Main Beam Dump is designed based on 1TeV Beam Parameters.
How much thermal load would be relaxed with 250GeV nominal status?

	250GeV nominal	1TeV Energy upgrade
Beam Energy	125GeV	500GeV
Electrons per Bunch	$2x10^{10}$ (3.2nC)	$1.74x10^{10}$ (2.79nC)
Bunches per Pulse	1312	2450
Beam Size	σx = 2.42mm, σy = 0.27mm @ Beam Dump entrance	
Beam divergence	1μrad @Beam Dump entrance	
Momentum spread	0.2% Beam Dump entrance	
Pulse length	0.727ms	0.897ms
Pulse Energy	0.52MJ	3.41 MJ
Rep rate	5Hz	4Hz
Average Power	**2.6 MW**	**13.7 MW**

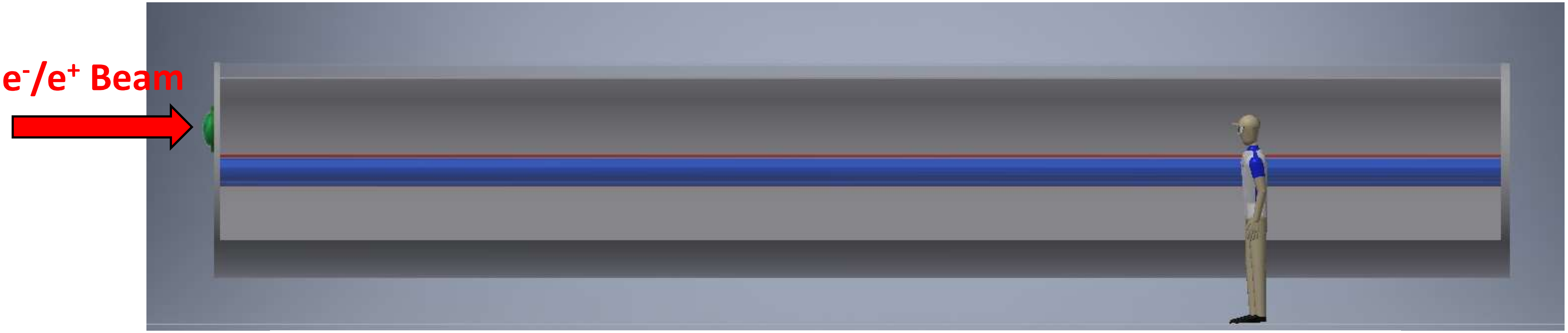
Contents

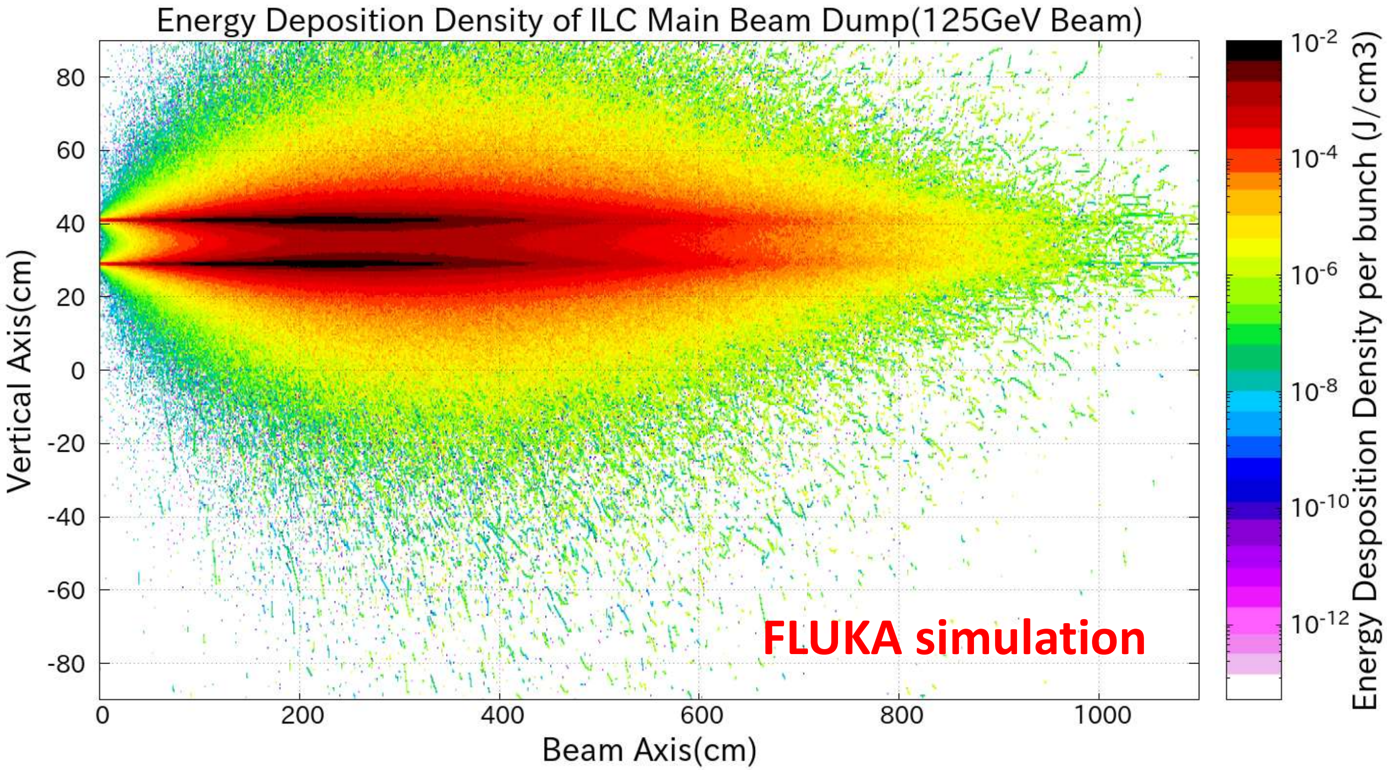
- **Thermal Analysis**
  - Energy deposition
  - Peak temperature in water flow
  - Pressure wave in water
  - Beam window durability
- **Water Activation**
- **Required System**
  - Pump system
  - Recombiner system
  - Water filtering
  - Shielding for prevention of activation

Thermal Analysis

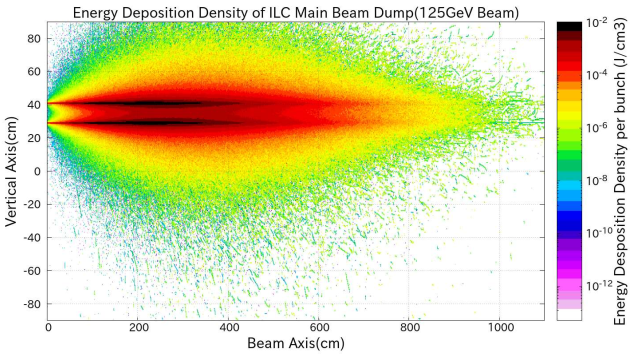
Energy Deposition in water– Side View

[Energy Deposition in water]



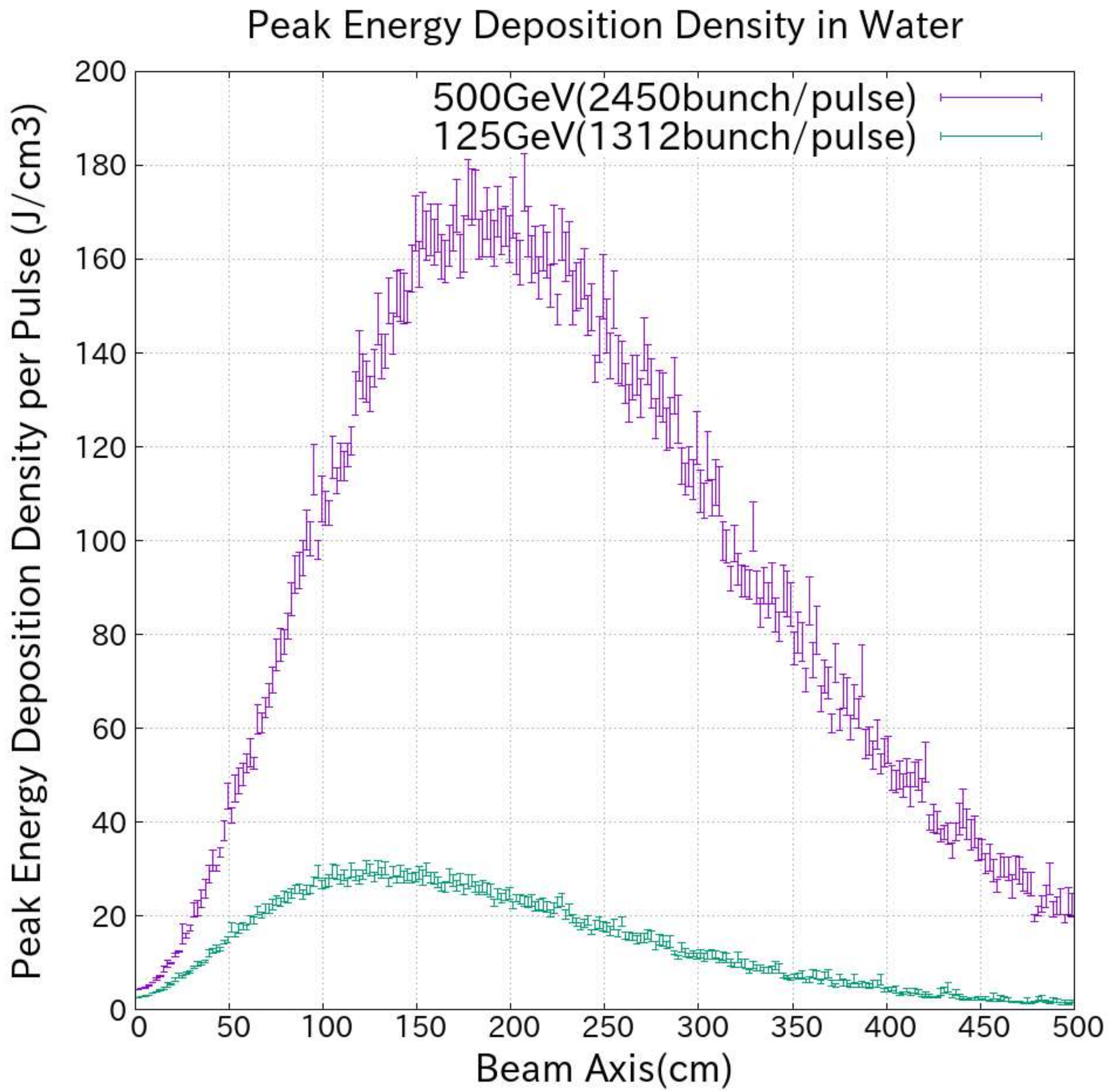


Peak Energy Deposition Density



Max value along beam axis

FLUKA simulation



【250GeV nominal】

Max PEDD = 28J/cm3

@ Z=125cm

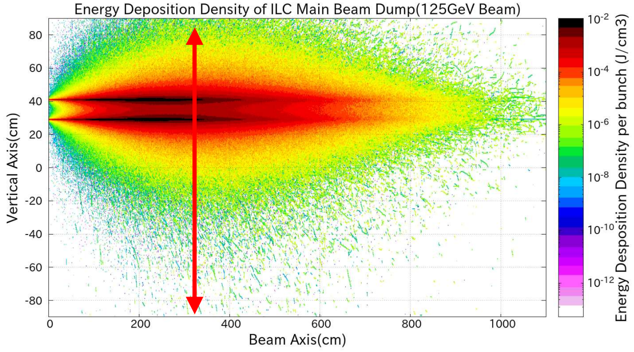
【1TeV stage】

Max PEDD = 170J/cm3

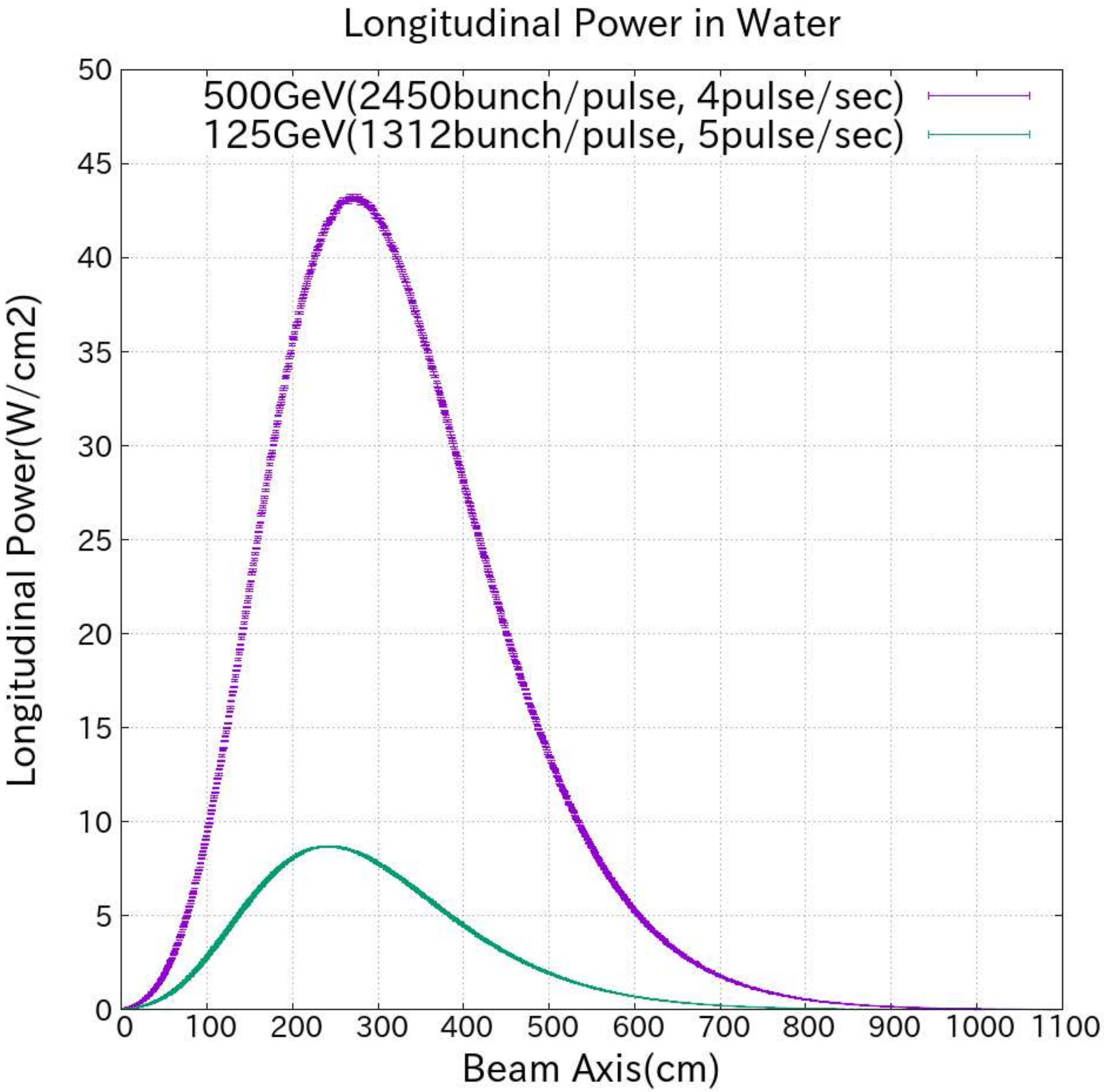
@ Z=190cm

Longitudinal Power

FLUKA simulation



Integrate transverse



【250GeV nominal】

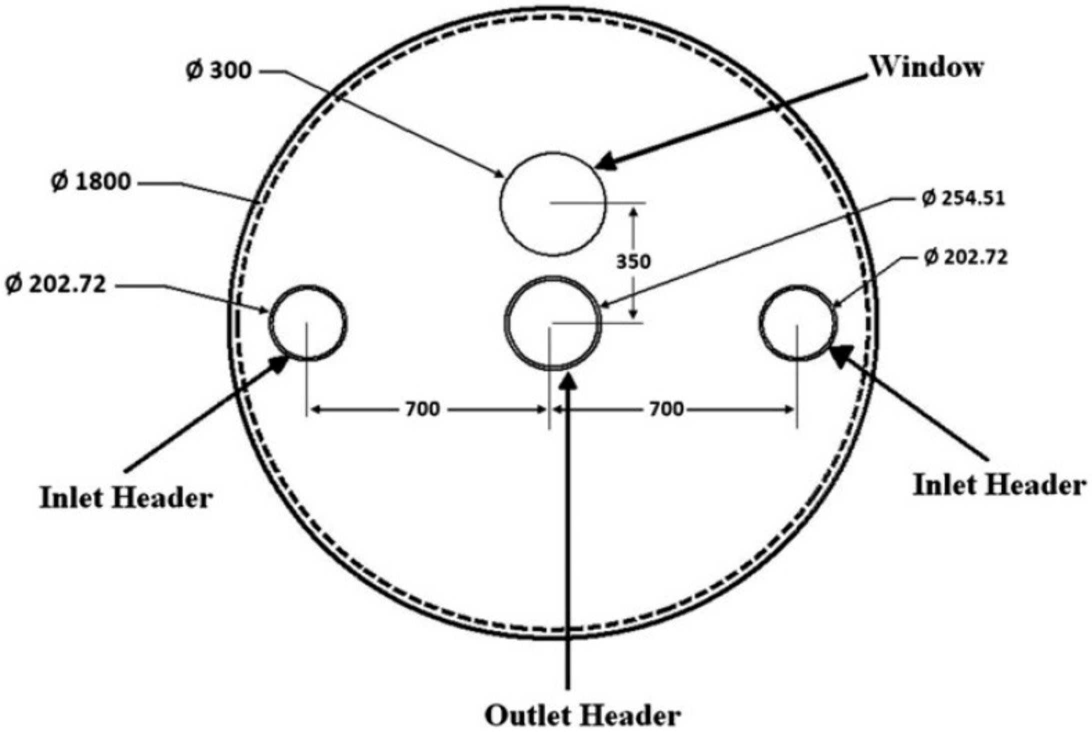
Max Longitudinal Power = 43kW/cm @ Z=280cm

【1TeV stage】

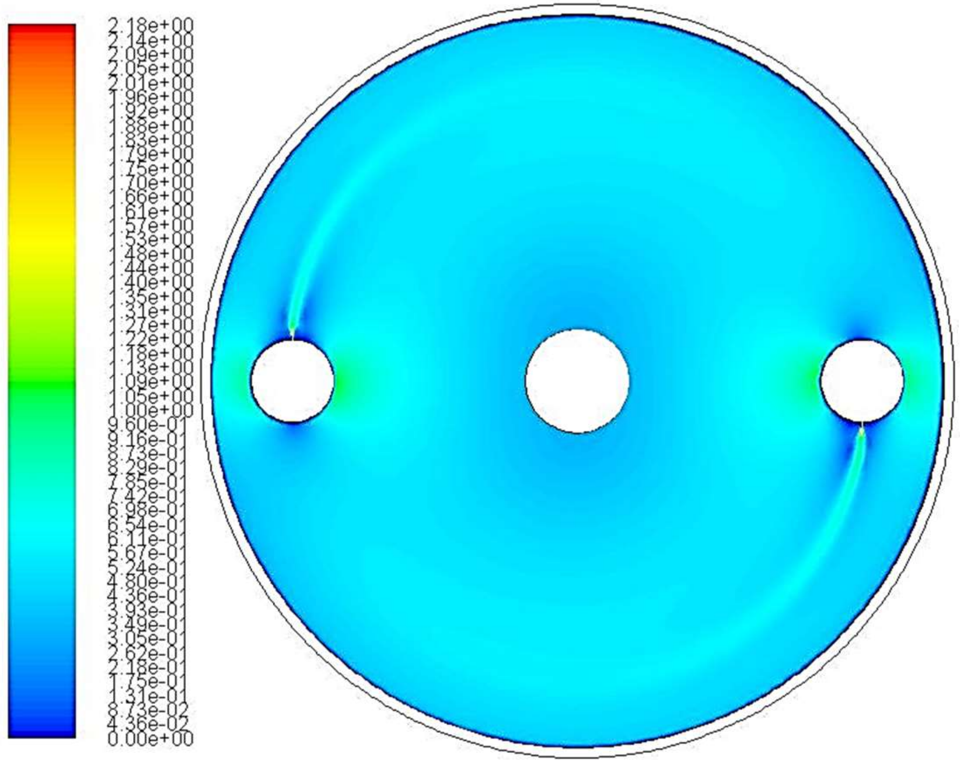
Max Longitudinal Power = 8.4kW/cm @ Z=230cm

Temperature Evaluation

Geometry



Flow Velocity

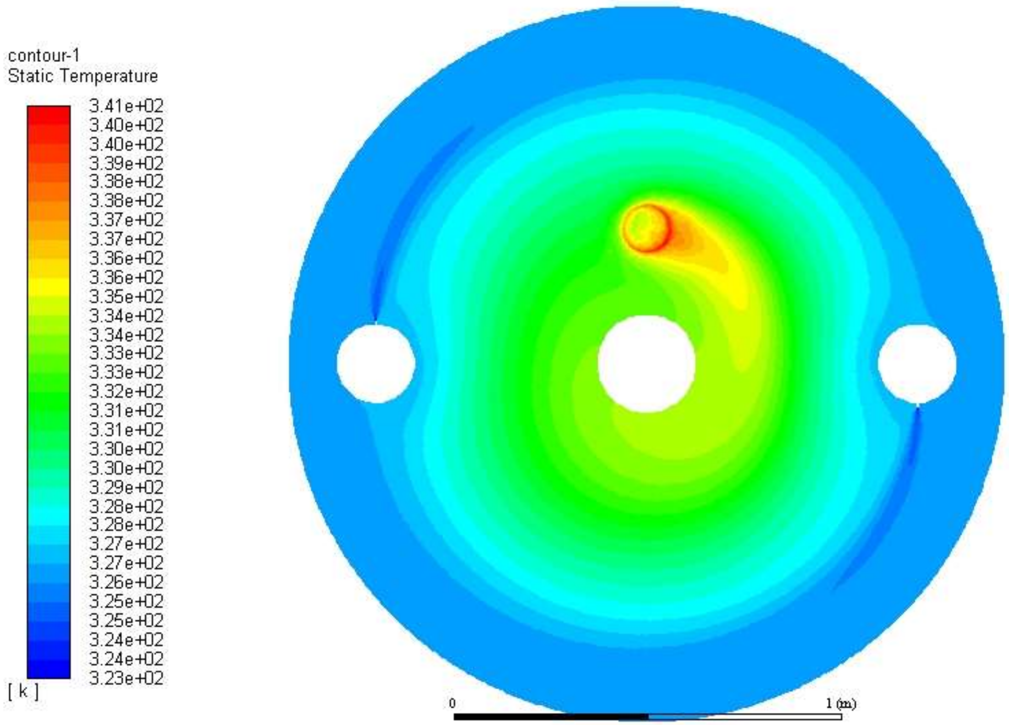


- **CFD calculation (ANSYS-FLUENT)**
- **2D analysis where peak longitudinal power is observed.**
  Z=230cm for 250GeV nominal, Z=280cm for 1TeV status.
- **Beam heat is Imported from FLUKA data to each cells.**

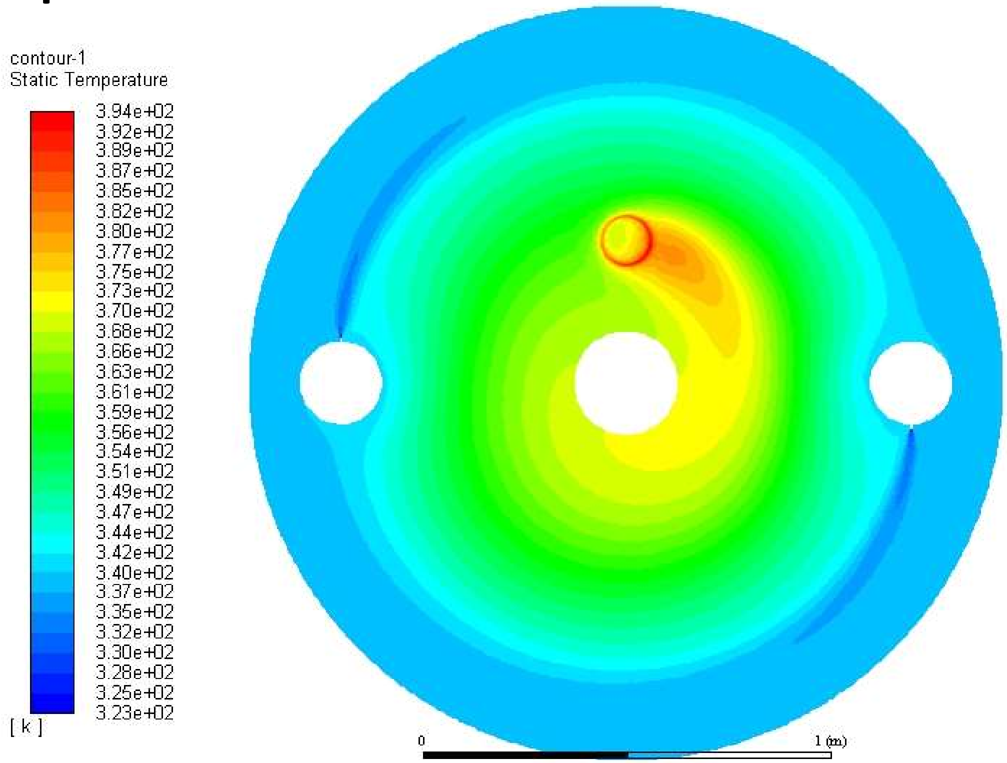
ANSYS simulation

Max Temperature

Temperature Distribution when Beam pulse complete



250GeV nominal Status
(125GeV, 1312bunch/pulse, 5pulse/sec)



1TeV Status
(500GeV, 2450bunch/pulse, 4pulse/sec)

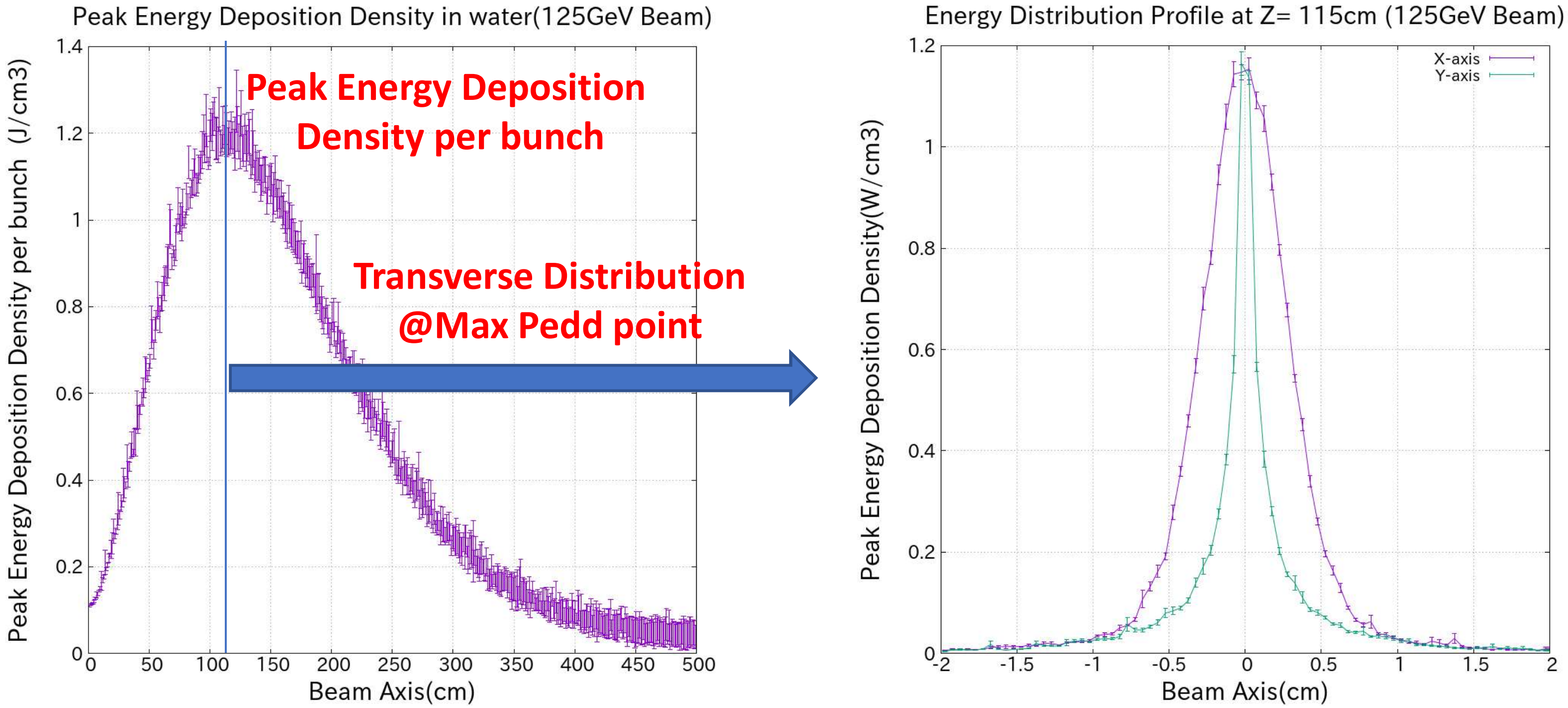
【Max Temperature】250GeV-nominal : 68℃ , 1TeV : 121℃

Pressure Wave in Water

1bunch energy deposition in water

Pressure rise is occurred by thermal expansion and propagate as pressure wave.

In water of main beam dump, pressure wave is generated by each bunch.



- **Max PEDD : 1.2J/cm3 @Z=115cm**
- **Heat Distribution @Z=115cm : σx=2.55mm, σy=0.53mm**

Pressure wave simulation

◆ Pressure Wave Evaluation

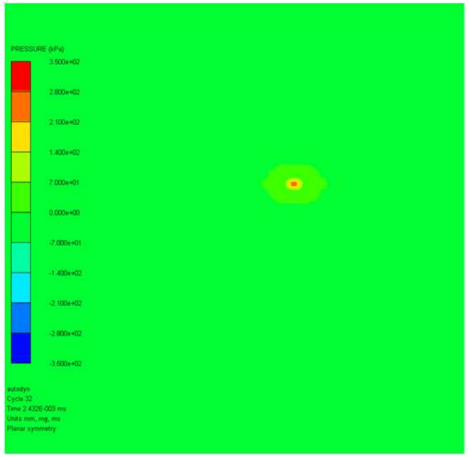
・ Mie Gruneisen Shock Equation $P = P_H + \Gamma\rho(e - e_H) \quad \Rightarrow \quad \delta P = \Gamma\rho\delta e$

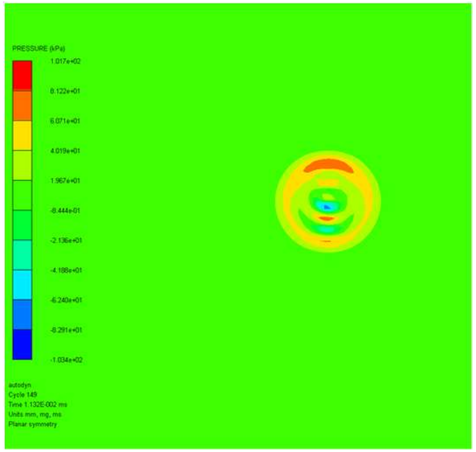
Γ:Gruneisen Gamma, ρ : density, e : energy deposition density
Γ=0.32 for 60℃ water

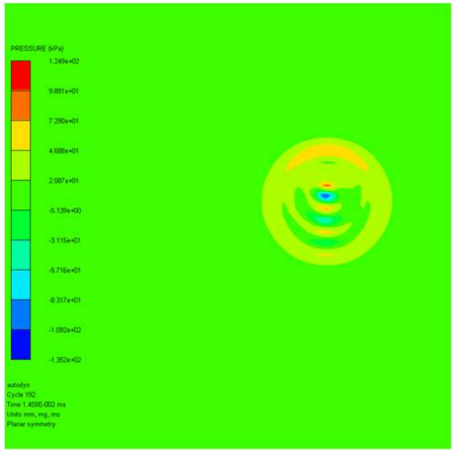
⇒ 1bunch pressure rise dP=0.32×1.2J/cm3 = 3.84bar

◆ Pressure Wave Simulation

・Thermal shock can be evaluated by Hydrocode(This time, I used Autodyn).
・2D simulation @Peak Energy Deposition density observed(Z=115cm) to evaluate the negative pressure in water(Cavitation)

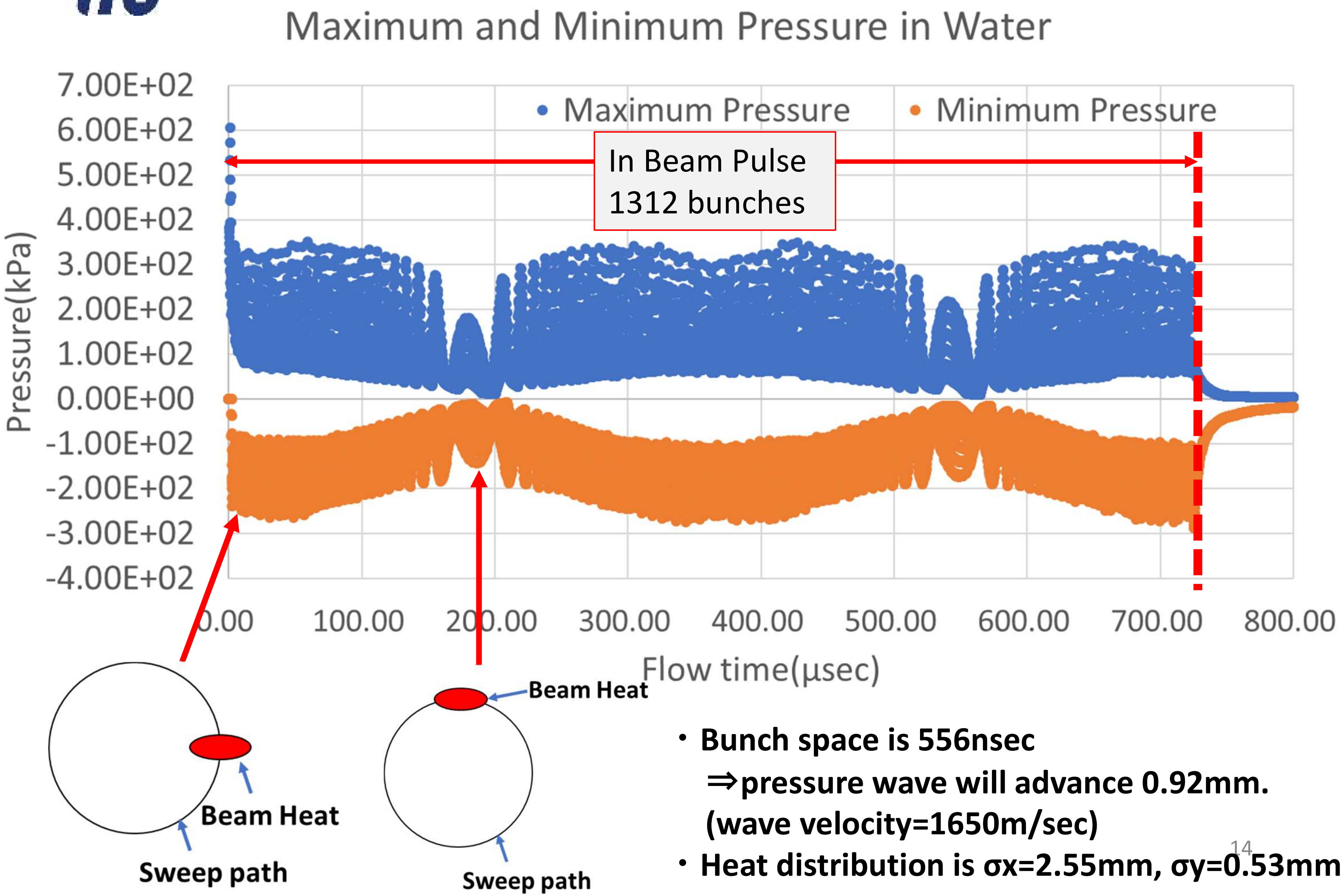






ANSYS simulation

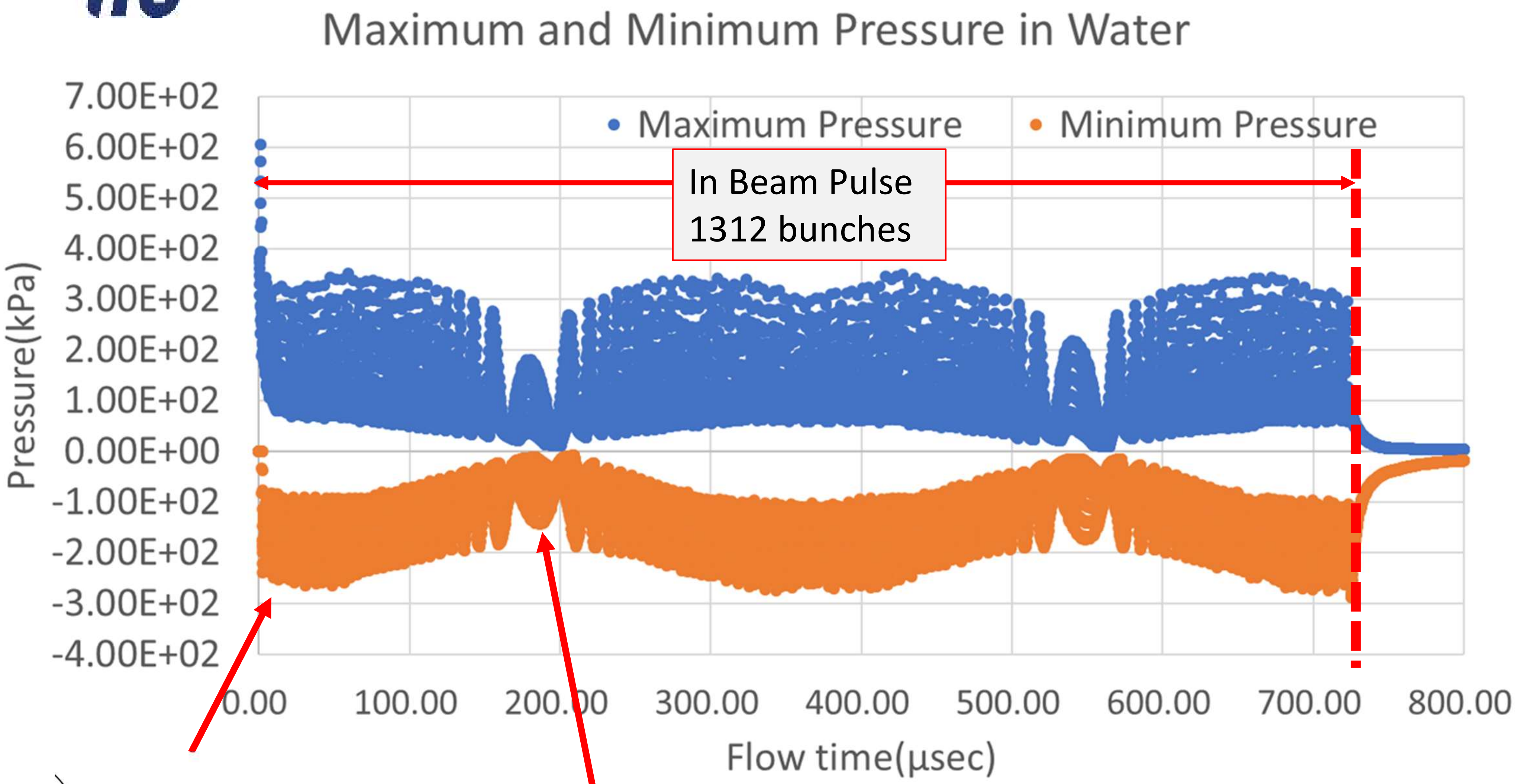
Max and Min Pressure Intensity

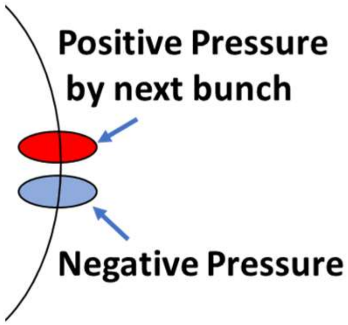


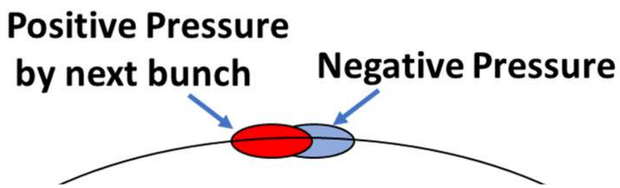
- Bunch space is 556nsec
  ⇒pressure wave will advance 0.92mm.
  (wave velocity=1650m/sec)
- Heat distribution is σx=2.55mm, σy=0.53mm.

ANSYS simulation

Max and Min Pressure Intensity



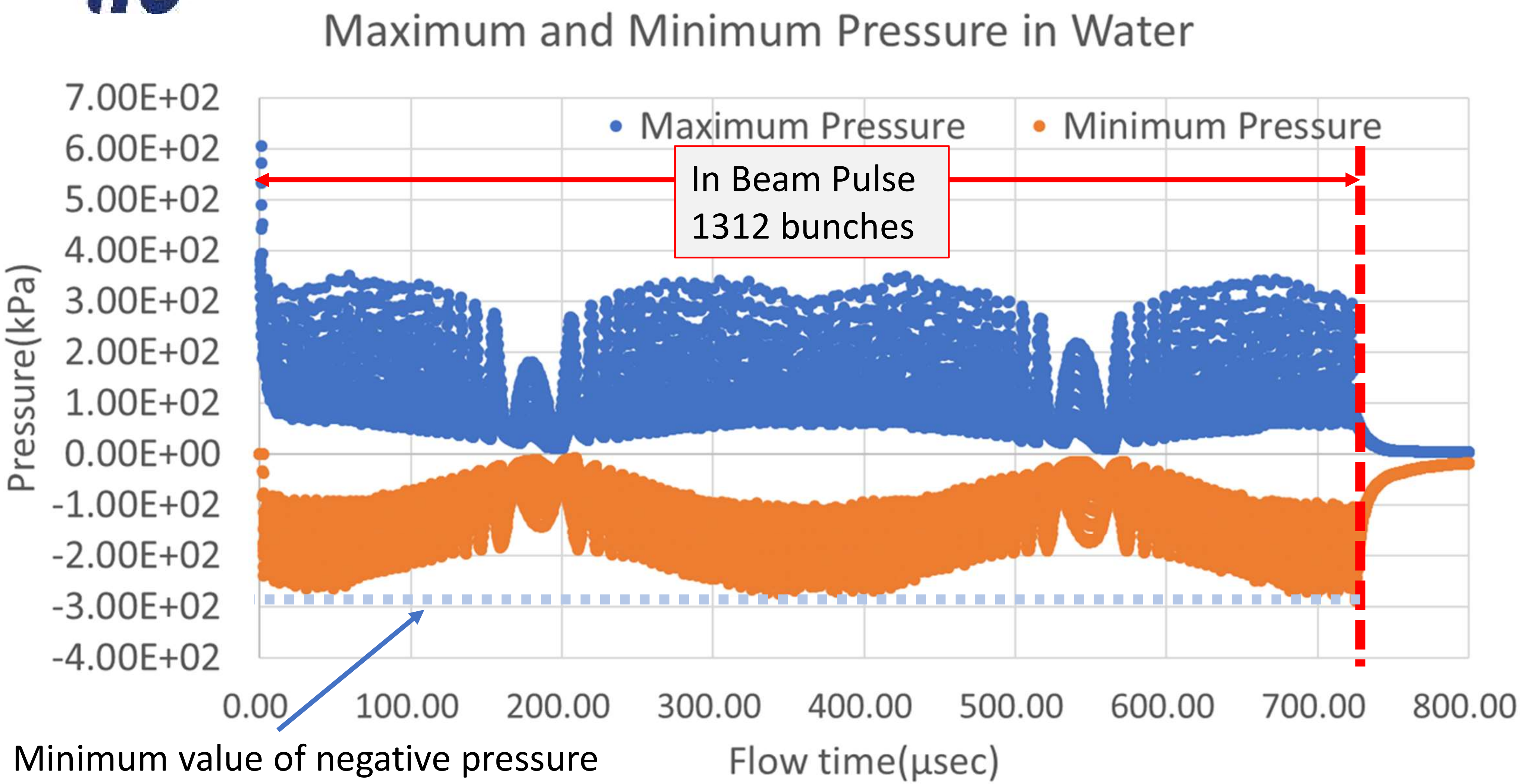




- **Bunch space is 556nsec**
  ⇒pressure wave will advance 0.92mm.
  (wave velocity=1650m/sec)
- **Heat distribution is σx=2.55mm, σy=0.53mm.**

ANSYS simulation

Max and Min Pressure Intensity



Highest Pressure : 6.2 bar , Lowest Pressure : -2.8bar

Beam Window

(Detail : LCWS2017 “Simulation Study of ILC Main Beam Dump Window”)

Heat Load of Beam Window

Nominal

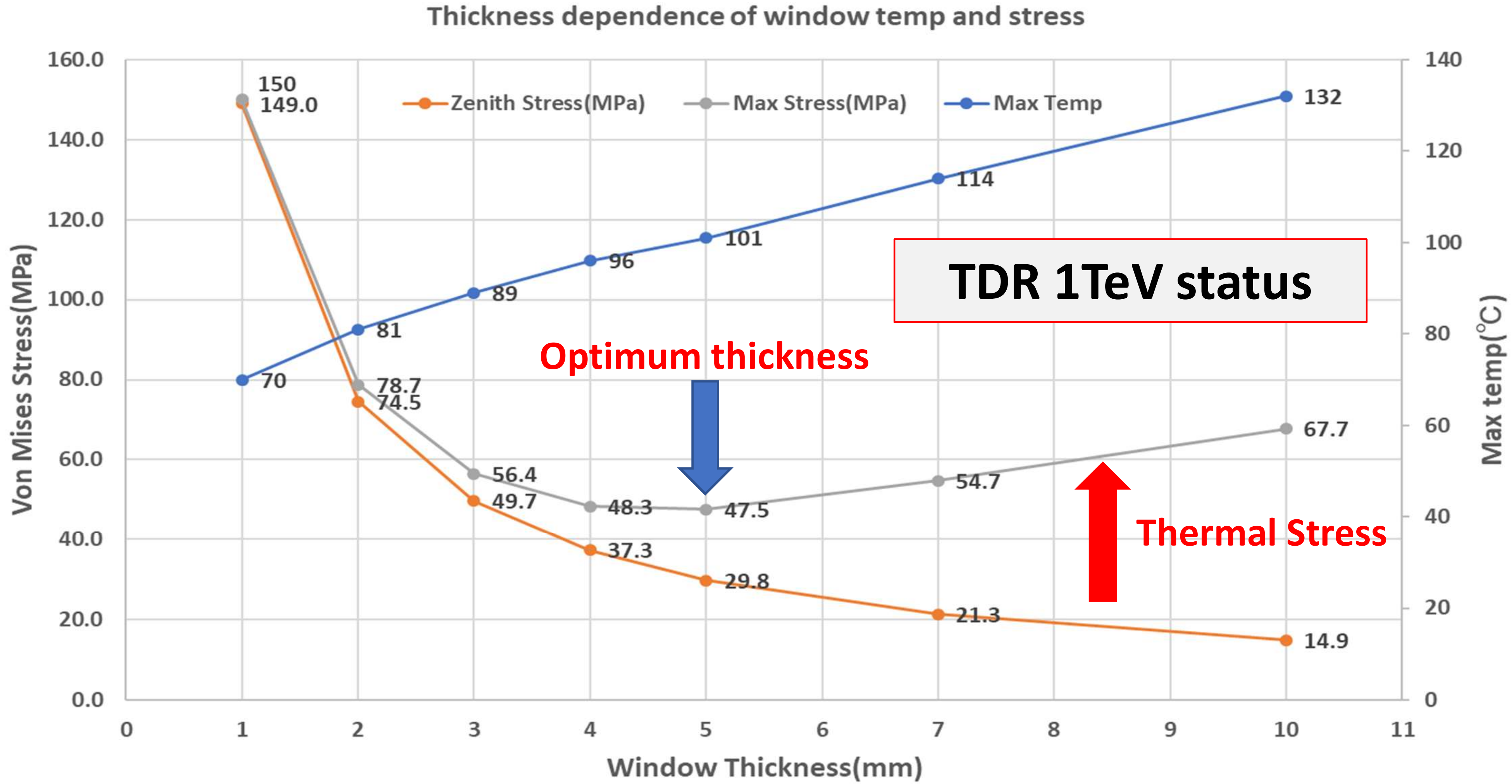
	250GeV nominal	500GeV TDR baseline	500GeV Lum. Upgrade	1TeV Energy upgrade	1TeV TDR design
Beam Energy	125GeV	250GeV	250GeV	500GeV	500GeV
Electrons per Bunch	2×10^{10} (3.2nC)	2×10^{10} (3.2nC)	2×10^{10} (3.2nC)	1.74×10^{10} (2.79nC)	2×10^{10} (3.2nC)
Bunches per Pulse	1312	1312	2625	2450	2820
Pulse Energy	0.52MJ	1.05 MJ	2.10 MJ	3.41 MJ	4.5MJ
Rep rate	5Hz	5Hz	5Hz	4Hz	4Hz
Average Power	2.6 MW	5.25 MW	10.5 MW	13.7 MW	18MW
Max Energy deposition density per pulse	**10J/cm3 Δ3.9℃**	10J/cm3 Δ3.9℃	**20J/cm3 Δ7.7℃**	16.3J/cm3 Δ6.3℃	22.5J/cm3 Δ8.3℃
Total deposition power	**14.2W**	14.2W	**28.5W**	18.5W	24.5W
Max DPA value Per pulse	**1.1×10^{-9}**	1.1×10^{-9}	**2.1×10^{-9}**	1.7×10^{-9}	2.3×10^{-9}
DPA after 5000hour	**0.1**	0.1	**0.19**	0.12	0.17

The most severe condition

- **Compare to TDR 1TeV status, Heat load of 250GeV nominal is 42%↓ decreased.**

Stress vs window thickness

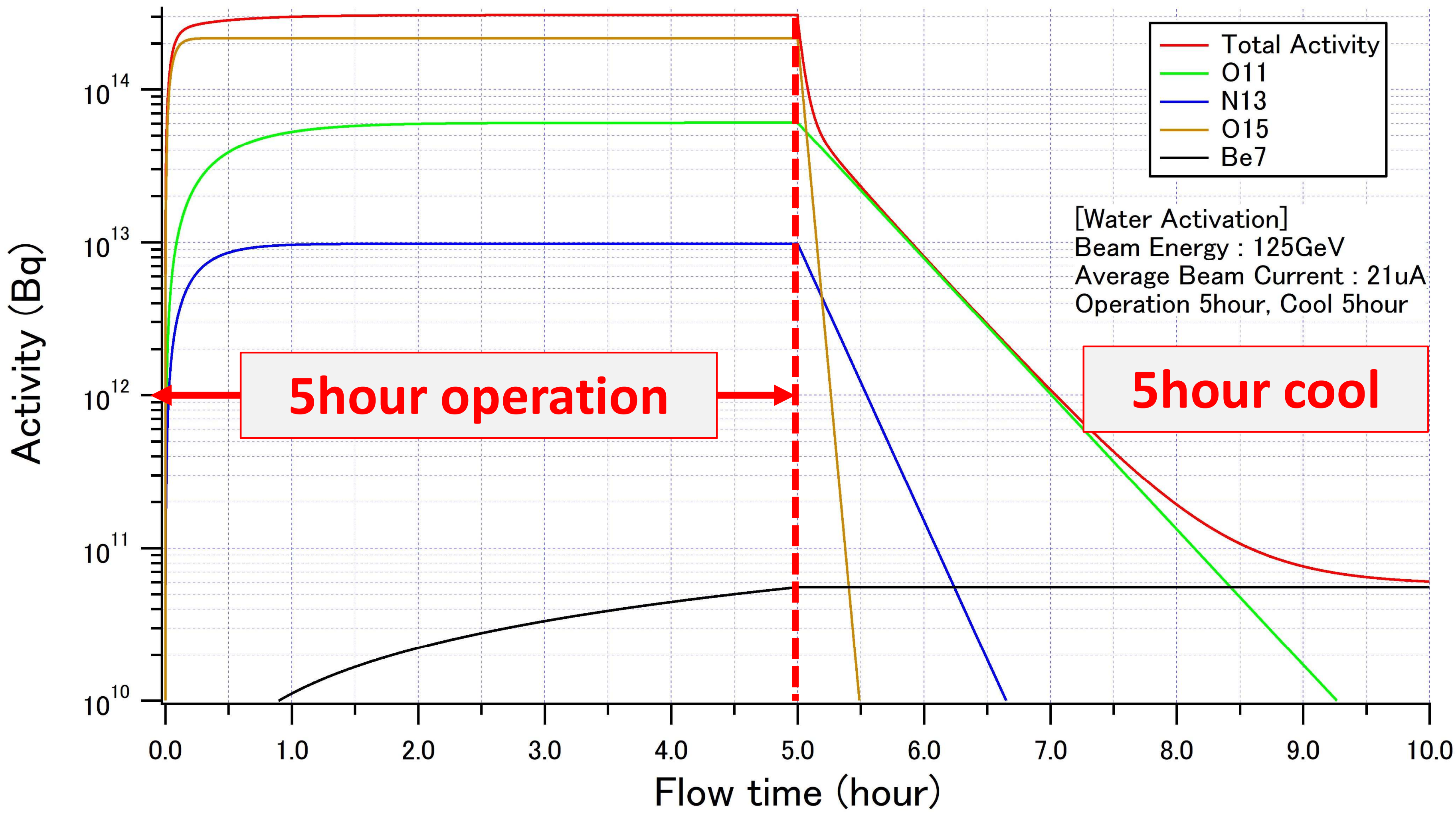
[Simulation Results : Von Mises Stress] **Heat transfer rate：500W/m2K**



- **Window material(Ti6Al4V) can withstand the stress of around 450MPa. Even if 1TeV status, 5mm thick window has safety factor of ~10.**

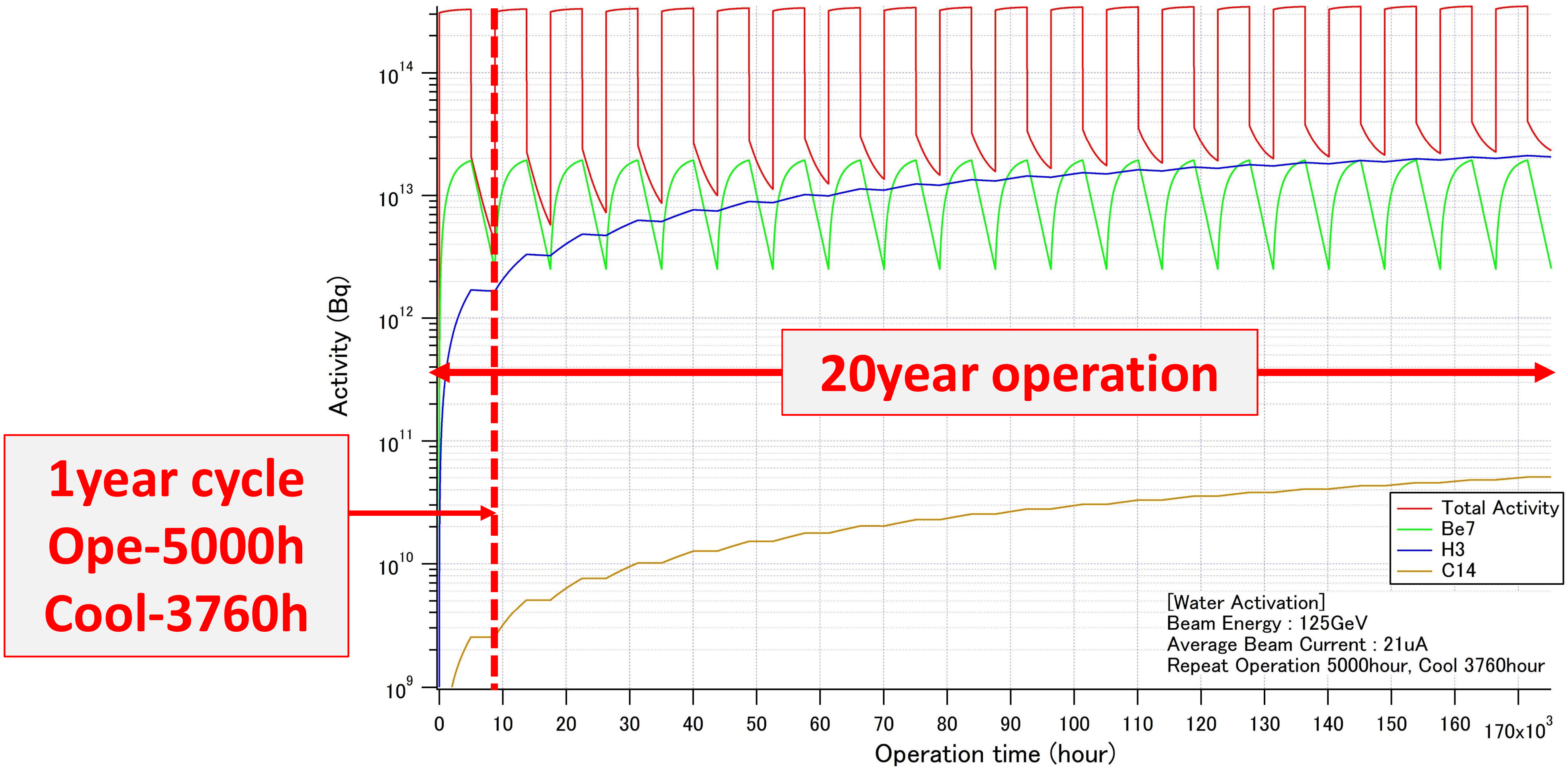
Water Activation

Radioactivity - short time scale



- **Short time scale(hours)**
  - **Major activities are, O11(half life:20min), N13(10min), O15(2min).**
  - **These activities are rapidly decreased. After 4hour cool, major activity will be Be7.**

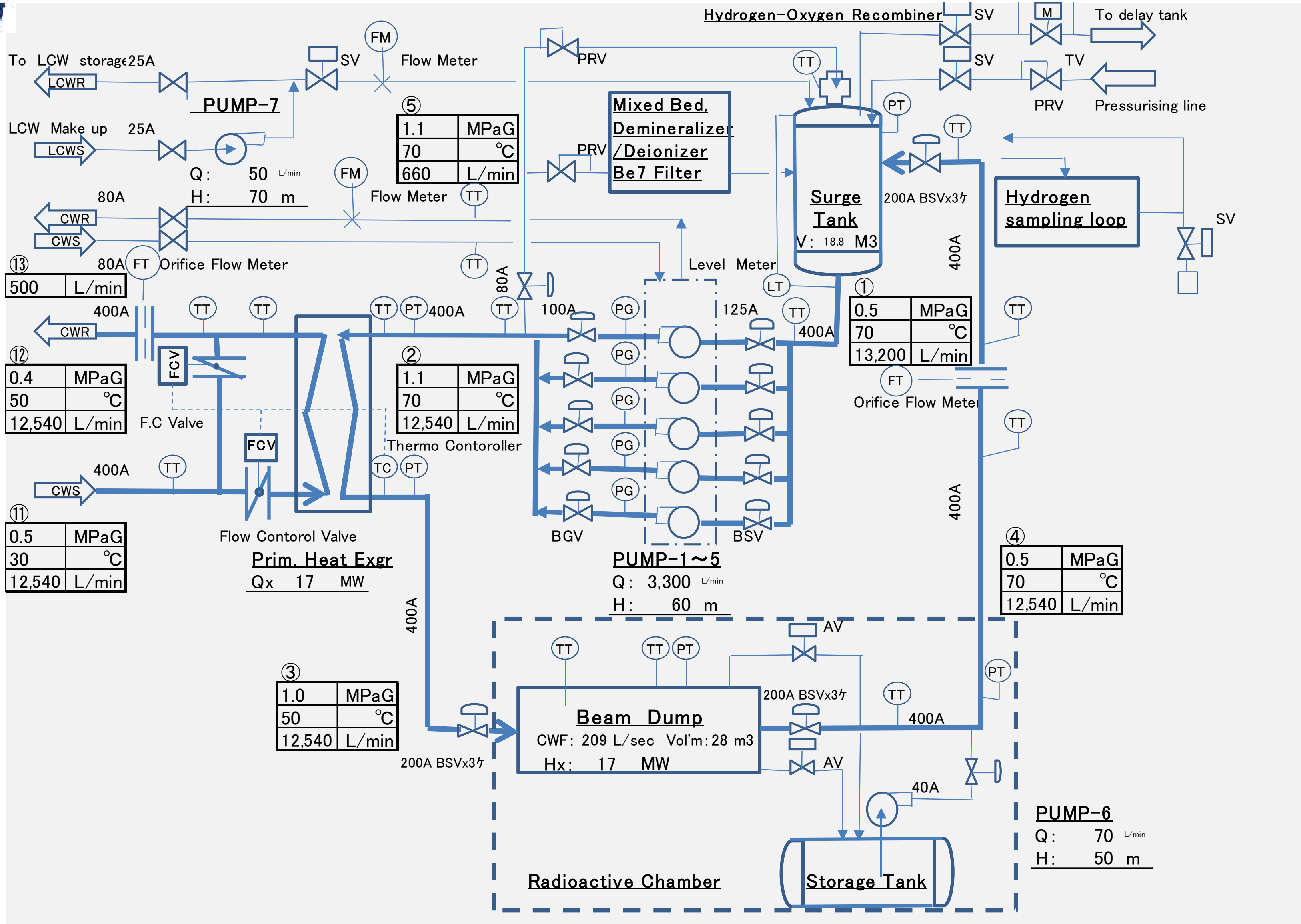
Radioactivity - long time scale



- **Long time scale(years)**
  - **Major activities are, Be7(half life:53day), H3(12.3y), C14(5.7e3y).**
  - **Saturation Activities are, Be7=2e13(Bq), H3=5.4e13, C14=3.7e13**
  - **Be7 is major component of gamma emitter(477keV) and will be saturated in 1year.**

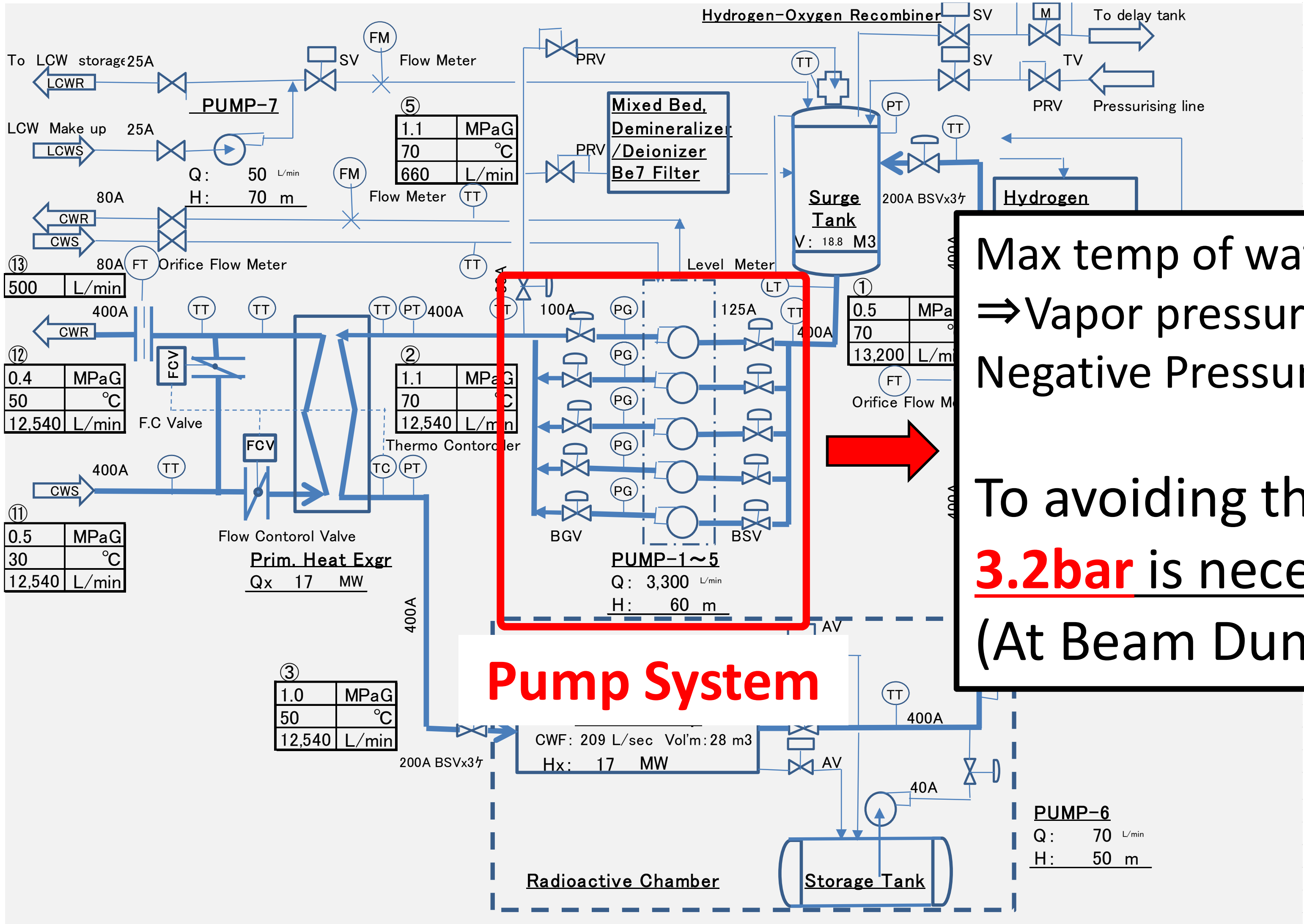
Required System
with 250GeV status

Cooling Water System



◆ **I started the discussion with qualified industry to make detailed design.**

Required Pressure



Max temp of water : ~70℃

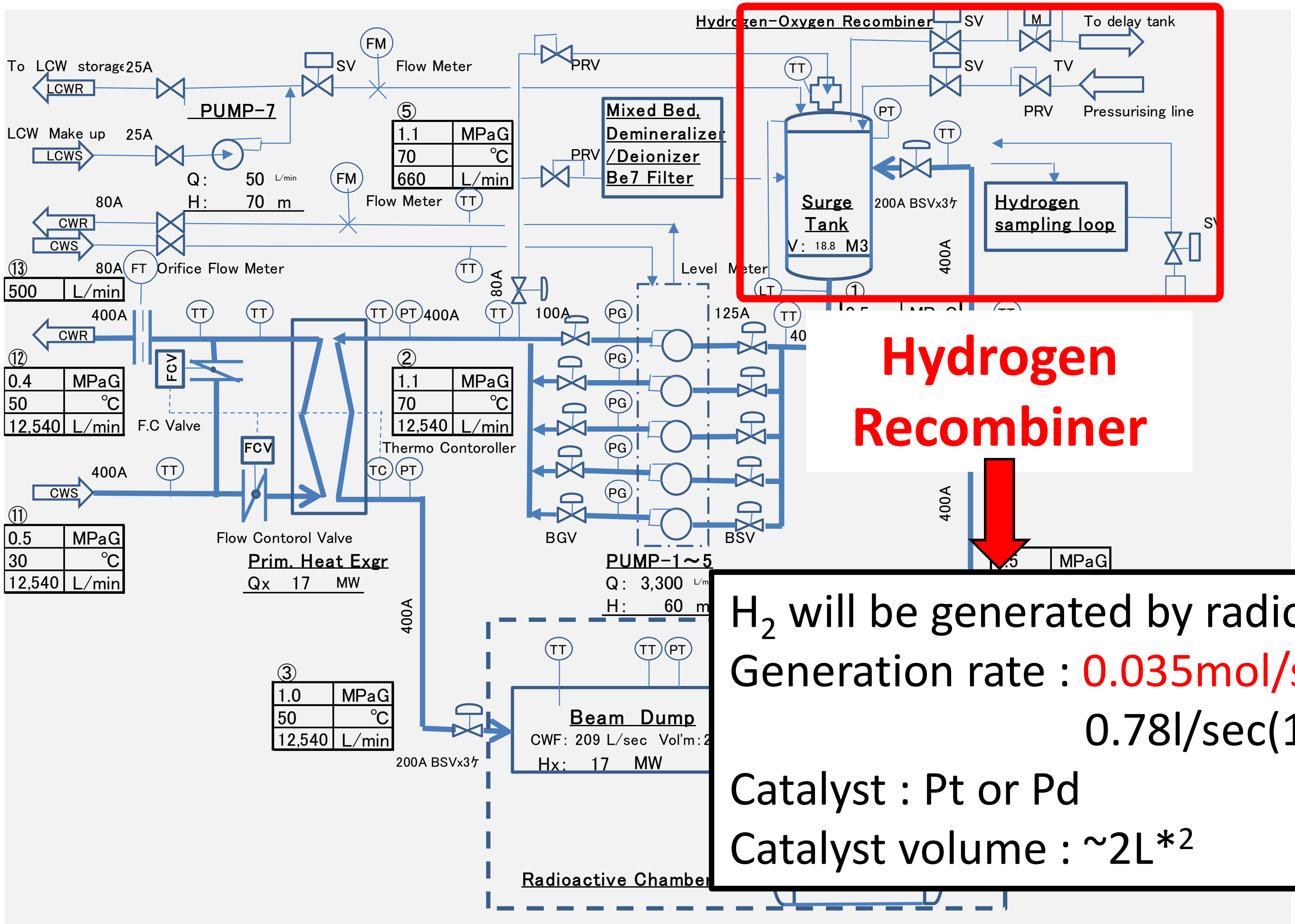
⇒Vapor pressure of 70℃ = 0.32bar

Negative Pressure : ~-2.8bar

To avoiding the partial boiling, **3.2bar** is necessary at least.

(At Beam Dump)

Hydrogen Recombiner



H$_2$ will be generated by radiolysis reaction.

Generation rate : 0.035mol/sec*1

0.78l/sec(1bar)

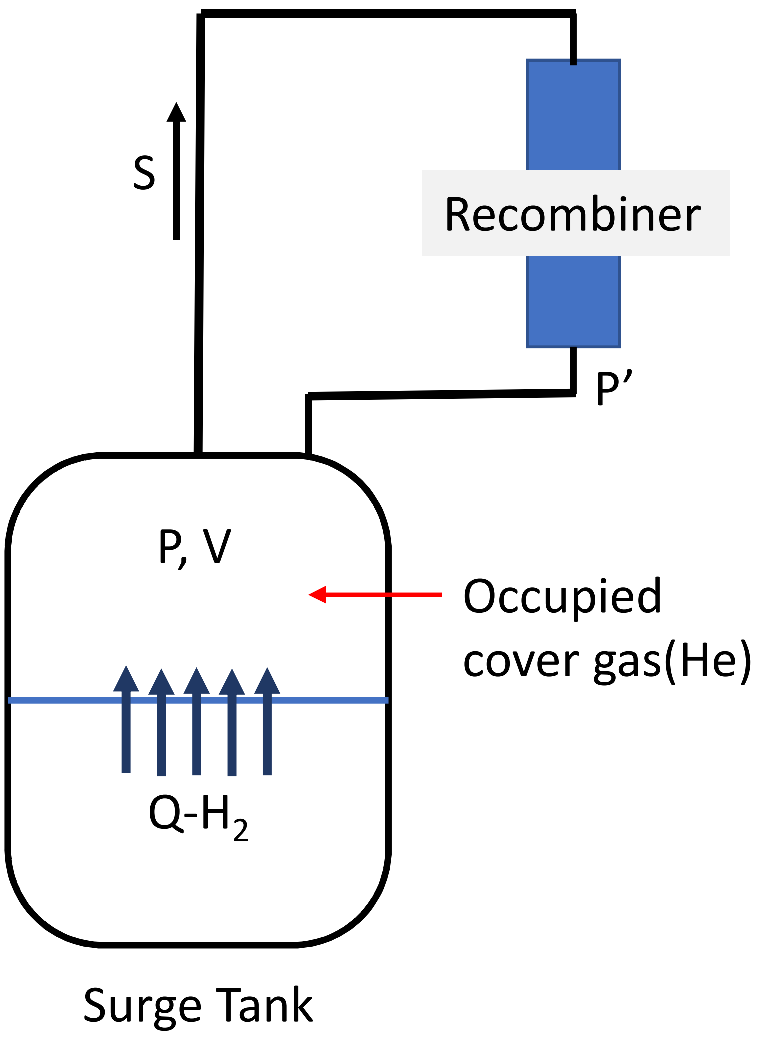
Catalyst : Pt or Pd

Catalyst volume : ~2L*2

*1 : scaled from SLAC experience : D.R. Walz and E.J. Seppi, Radiolysis and Hydrogen Evolution in the A-Beam Dump Radioactive Water System, SLAC-TN-67-29, October, 1967.

*2 : scaled from Base design of ILC Main Beam Dump : P. Satyamurthy, et.al., Design of an 18 MW vortex flow water beam dump for 500 GeV electrons/positrons of an international linear collider, NIM A 679 (2012)

Hydrogen Recombiner



◆ H_2 pressure

$$-V\frac{dP}{dt} = S(P-P') - Q$$

V:gas volume, S: volume flow, Q : gas generation velocity
P : pressure before recombiner, P' : pressure after recombiner

⇒steady state Q=S(P-P')

Q(H_2)=0.035*8.314*(50+273.15)=94Pa-m^3/sec

When recombine efficiency is 80%, P-P'=0.8P

Hydrogen Pressure(steady) P_{H2} = Q/(0.8 × S)

If S = 50L/sec (0.05m^3/sec), P_{H2}= 2350Pa

◆ Volume fraction of H_2

If cover gas pressure is 3bar,

Total Pressure : 302,350Pa

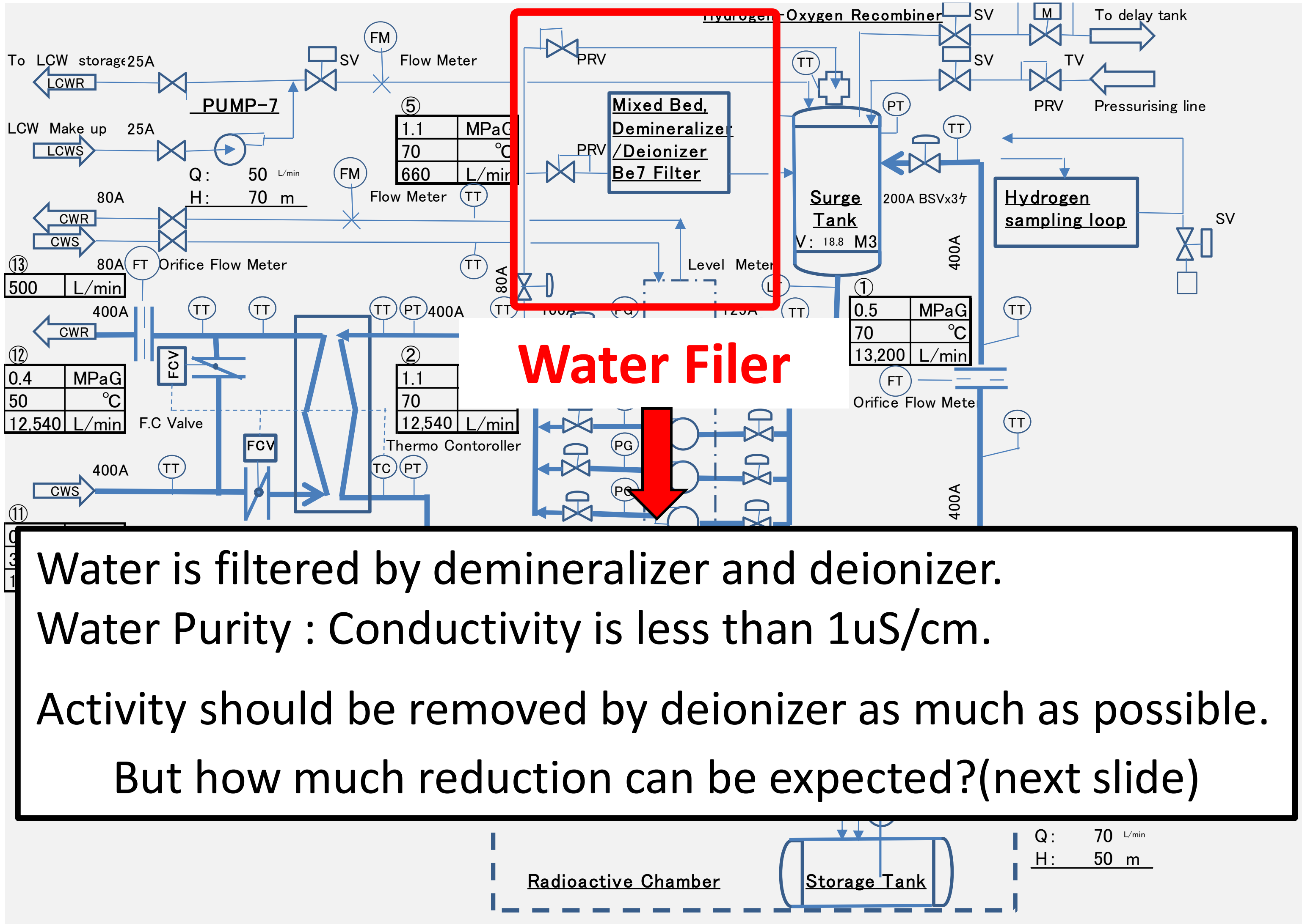
Volume fraction of H_2 : 2350/302350 *100

0.78 vol%

Lower Explosion limit of H_2 : 4 vol%

Required System : **Recombine Efficiency ~80%, Volume Flow ~50L/sec**

Water Filter



Water is filtered by demineralizer and deionizer.
Water Purity : Conductivity is less than 1uS/cm.

Activity should be removed by deionizer as much as possible.

But how much reduction can be expected?(next slide)

Water Activity Filtering

- **Base Status with 250GeV nominal status**

  1year Production(5000h) : Be7=2e13(Bq), H3=2e12

  Saturate Activity : Be7=2e13(Bq), H3=5.4e13

  Total water volume : ~50m^3

  Density in water without filter : Be7 = 4e5(Bq/cm^3), H3 = 1.1e6

- **Deionizer Performance**

  From J-PARC experience*, deionizer can remove 99.995% of Be7 in water.

  (Their deionizer system achieved to reduce Be7 from ~130GBq to ~6.5MBa)

  If our removal efficiency is 99.99%,,, Density in water with filter : Be7 = ~ 40(Bq/cm^3)

- **Deionizer Life Time and Shielding.**

  From J-PARC experience, deionizer can work several years.

  (Especially over 5year work at Neutrino Target & Horn system*)

  Deionizer retain 2e13Bq of Be7. Be7 emit 477keV gamma ray.

  ⇒Expected dose rate without shield is ~100mSv/h at 1m away(only Be7).

  Deionizer module needs shielding. Tenth value layer of Fe(500keV) = ~3cm

  ⇒ 12cm thick of Fe can reduce dose rate from 100mSv/h to 10uSv/hour at 1m away.

  Weight of deionizer (include the shield) would be several tons.

*Y.Oyama, T2K water drainage / exhaust air, Neutrino Beam Instruments 2014.

How much shield thickness is required?

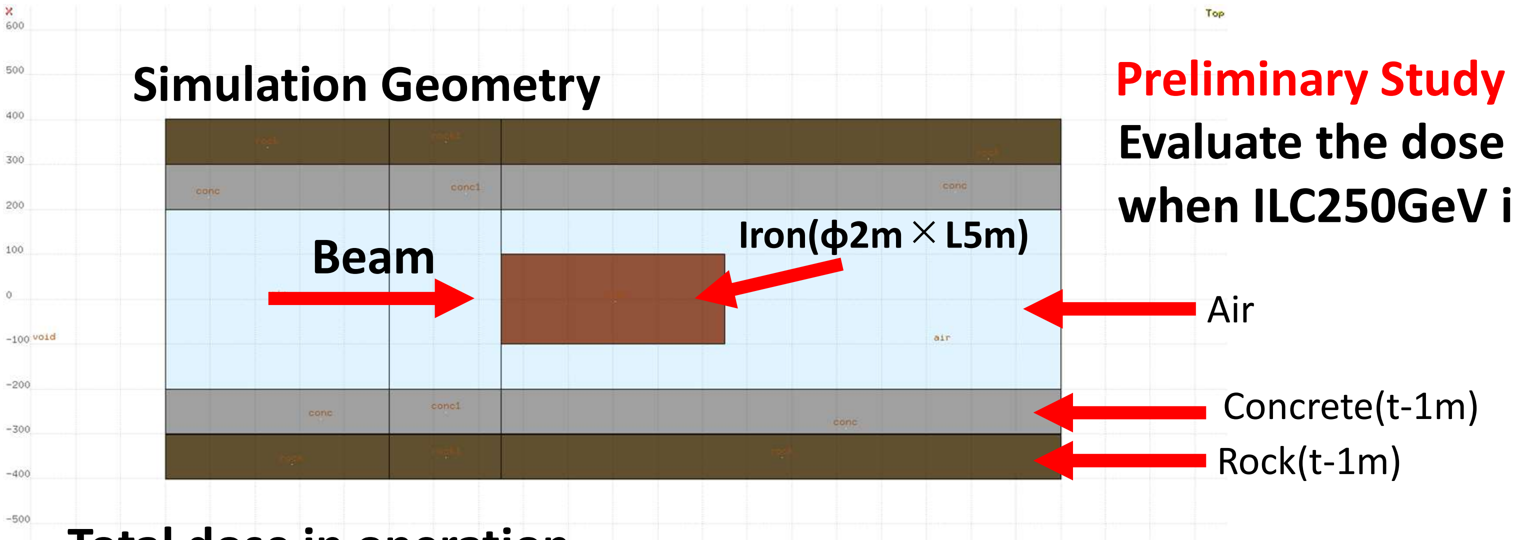
- **How much we should shield dose rate in operation?**

  Relation between Dose rate in operation and activation.

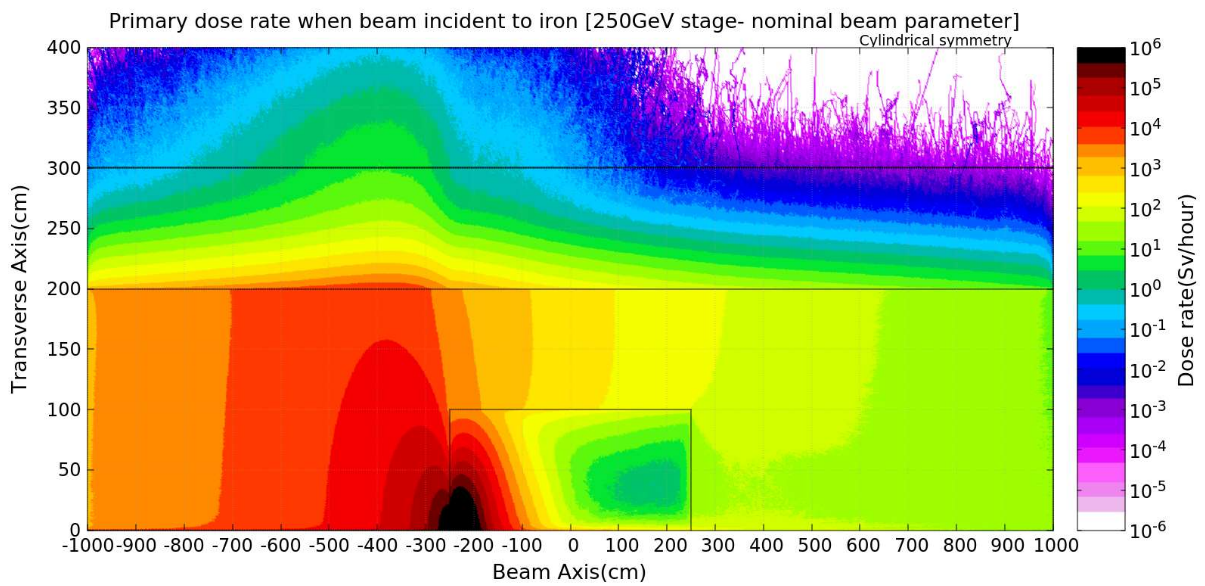
Preliminary Study

Evaluate the dose rate and activation when ILC250GeV incident to Iron

Simulation Geometry

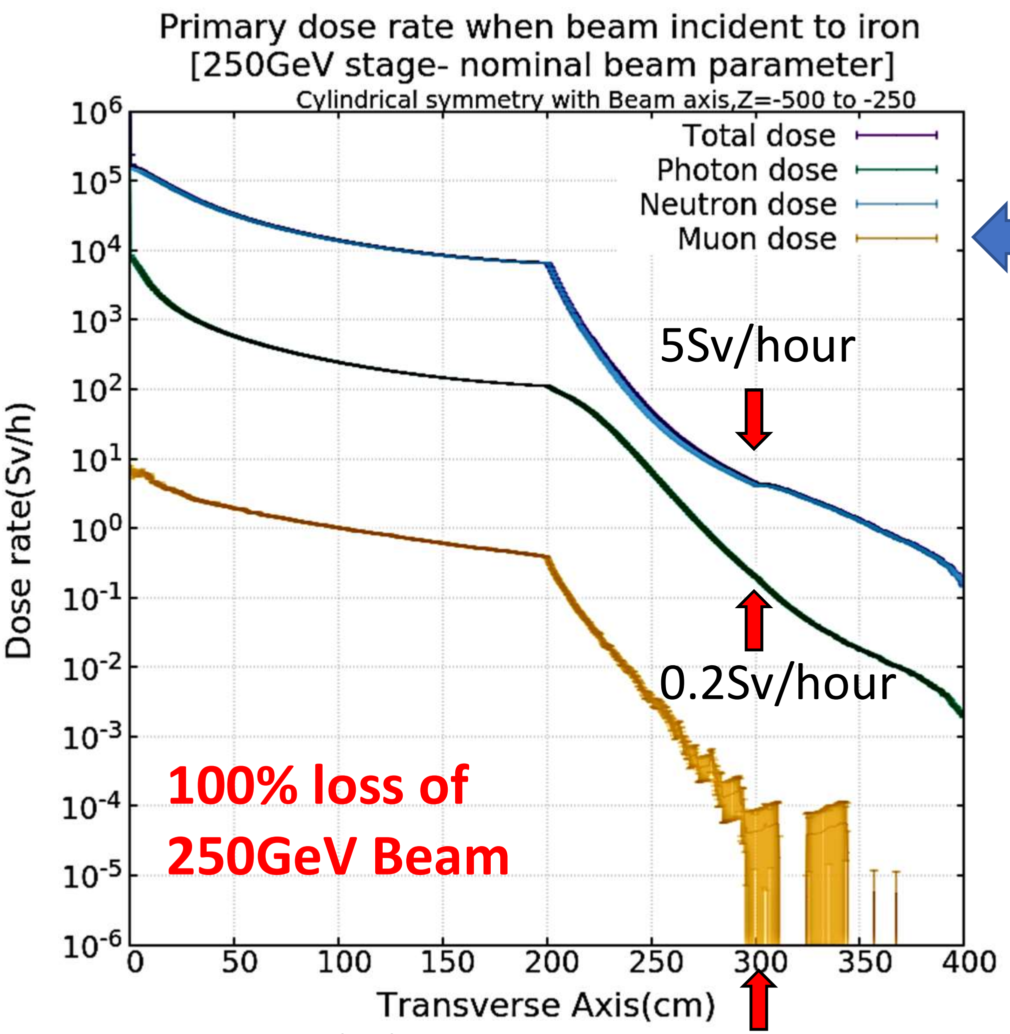


Total dose in operation



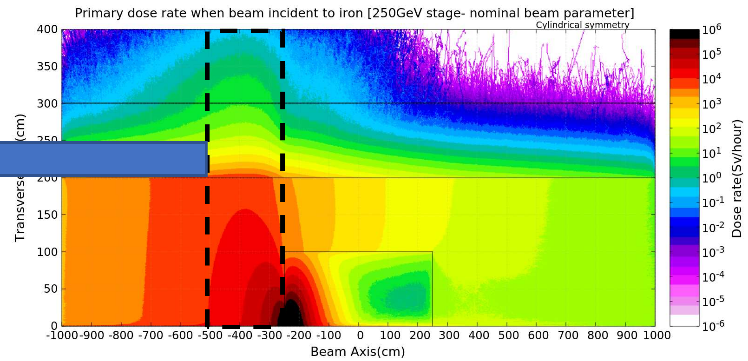
How much shield thickness is required?

- **How much we should shield dose rate in operation?**
  Relation between Dose rate in operation and activation.



Tunnel boundary

Preliminary Study

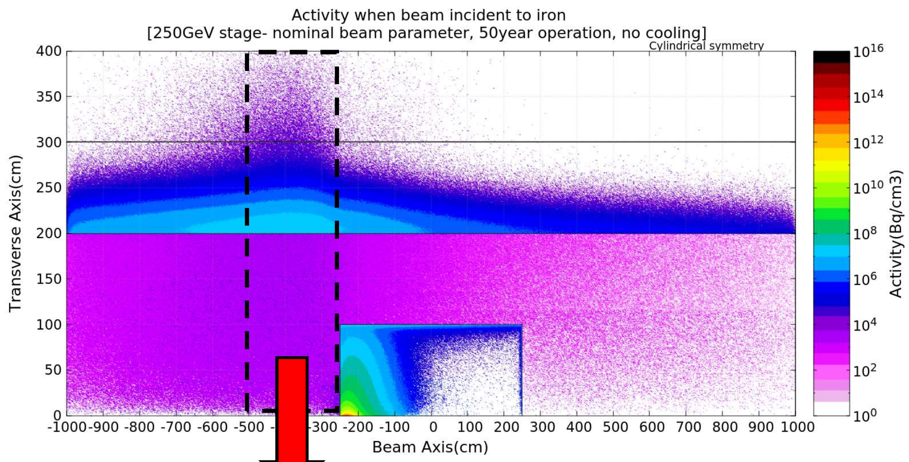


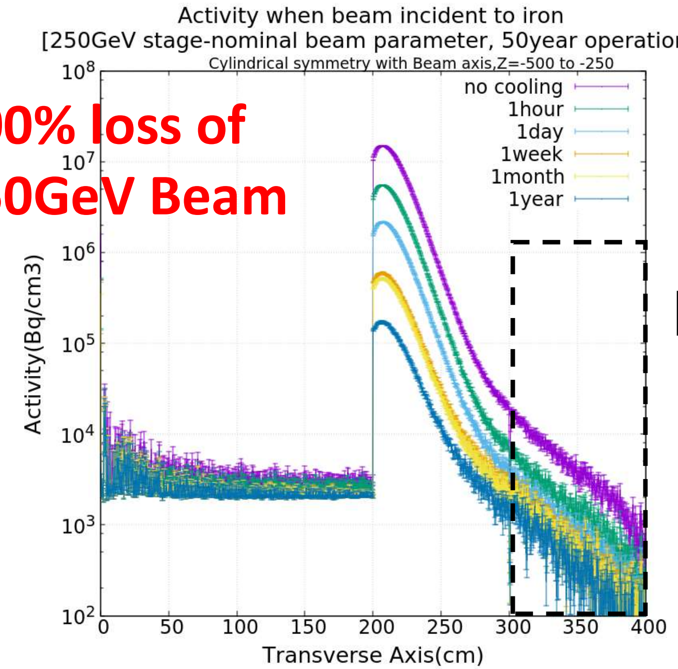
At tunnel boundary

Neutron is dominant : 96%

Total Activity in outside tunnel

◆ **Relation between Dose rate in operation and Activation.**





100% loss of 250GeV Beam

Ave Activity density (1m thick rock)

Preliminary Study

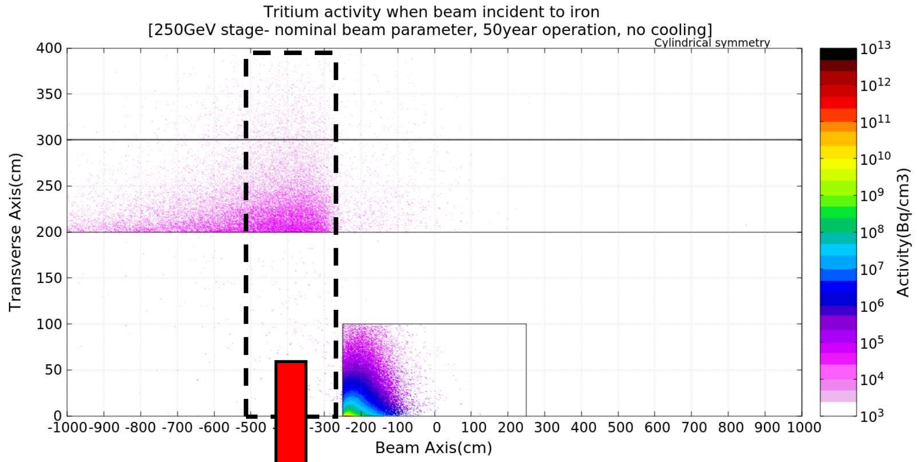
Total activity - 50year operation

Conversion to 5mSv/hour at boundary (0.1% loss)

Cooling	Average Activity(Bq/g) in Rock(t=1m)
None	2.23
1hour	0.82
1day	0.46
1week	0.32
1month	0.29
1year	0.20

H3 Activity in outside tunnel

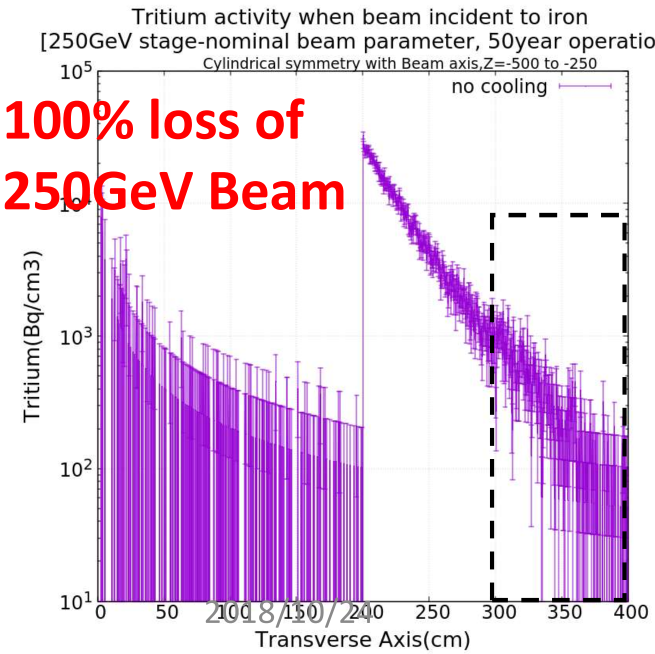
◆ **Relation between Dose rate in operation and Activation.**



Preliminary Study

H3 activity - 50year operation

100% loss of 250GeV Beam



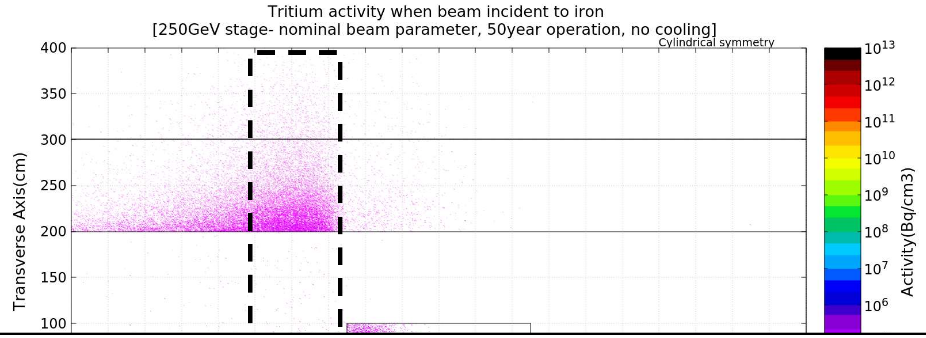
Ave Activity density (1m thick rock)

Conversion to 5mSv/hour at boundary (0.1% loss)

Average Activity(Bq/g) in Rock(t=1m)
0.14

H3 Activity in outside tunnel

◆ **Relation between Dose rate in operation and Activation.**



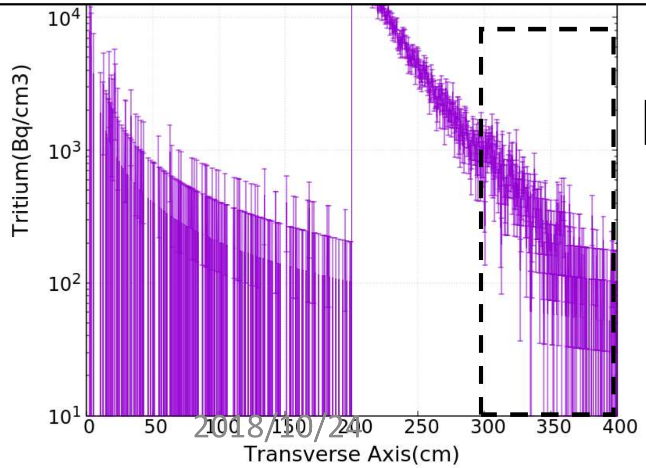
Preliminary Study

H3 activity - 50year operation

If Neutron dose rate at boundary = 5mSv/h is acceptable,

Main Dump shielding would be **iron 0.5 & concrete 4m**(1TeV OK)

(Detail : ALCW2018 "CFS consideration on the Main Dump and around")



(1m thick rock)

Average Activity(Bq/g) in Rock(t=1m)
0.14

Summary

Totally, situation is relaxed,,,

	250GeV nominal	1TeV-TDR
Max Temp in water	~70℃	~145℃
Required Pressure at dump	3.2bar at least	10bar But cavitation will occur
Window Heat Load per window thickness	14W/mm	25W/mm

(Relaxed factors are not only above)

Required systems are estimated and each one is not so special.

In 250GeV nominal stage, main dump can work with enough margin.
And we can check and learn many practical issues
for Luminosity and Energy upgrade !!