Thermal stress & cooling of J-Parc neutrino target

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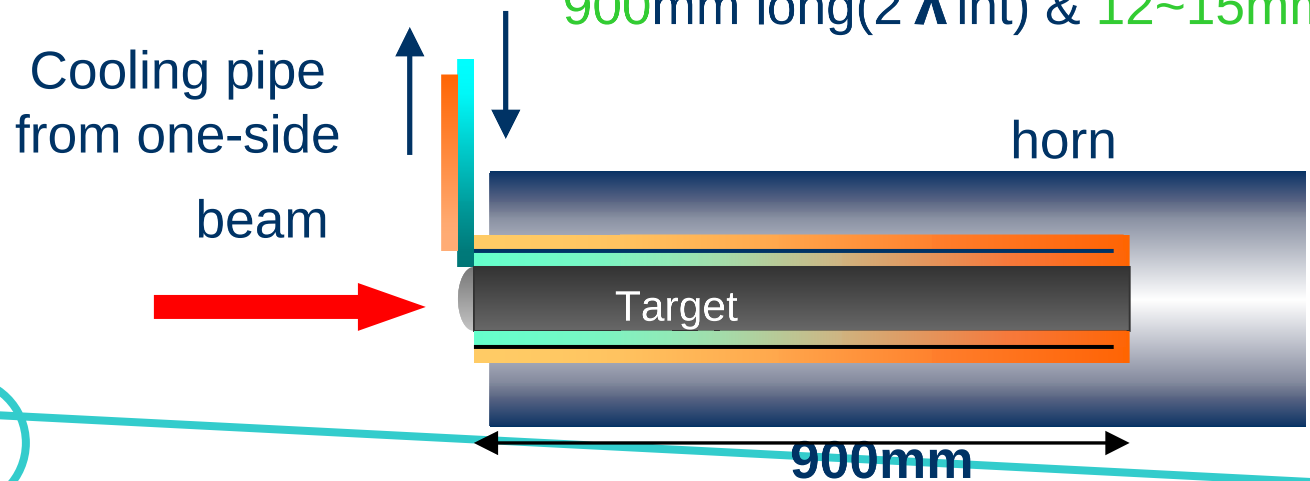
JHF target monitor R&D group

Introduction

- Beam: 50[GeV] proton, 0.75[MW]
  3×10^{14} [protons / spill] , 5[μsec/spill]
  3.3[sec](between spills) , 8[bunch/spill]
- Material: *graphite or C/C composite*
  Because of; high melting point(~3700℃)
  thermal resistance
- Cooling: water cooling
- Shape: cylindrical
  900mm long(2λint) & 12~15mm radius



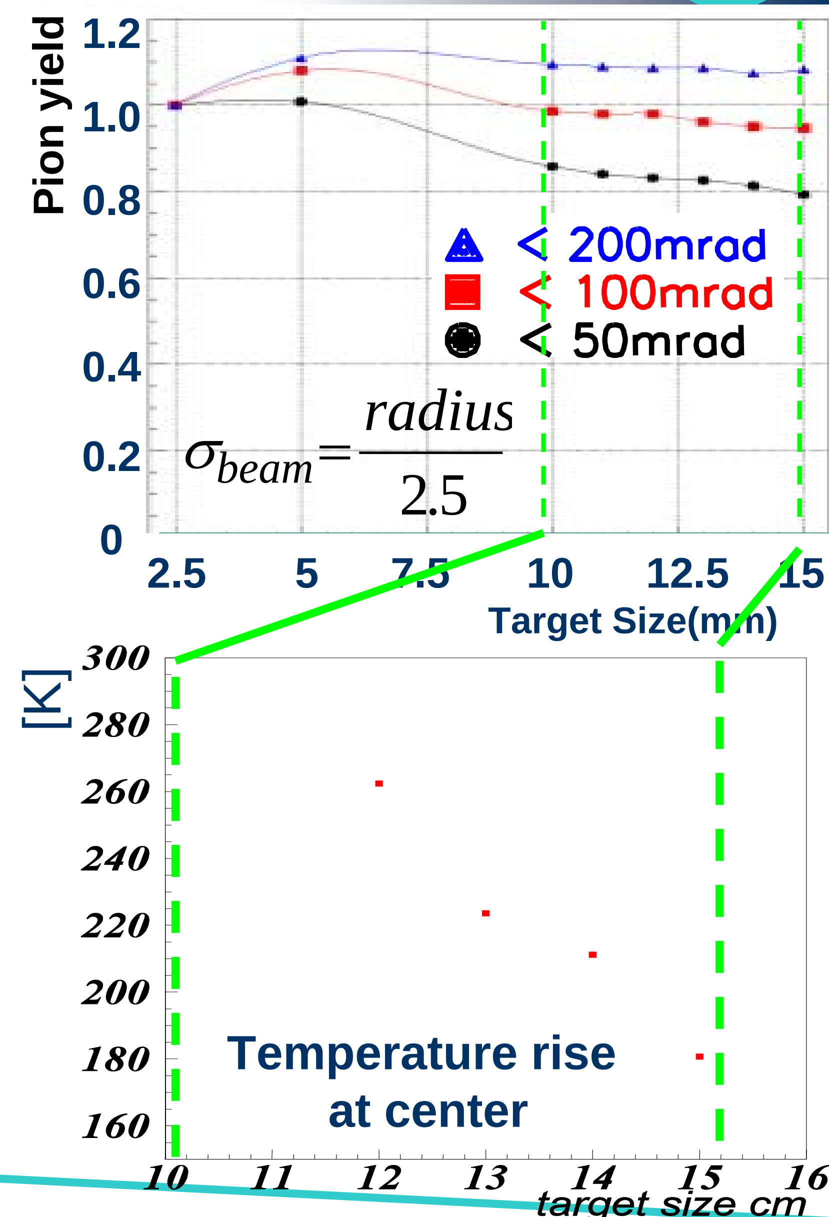
Requirements for target

- More pion
- Thermal shock resistance
- Possibility to cool

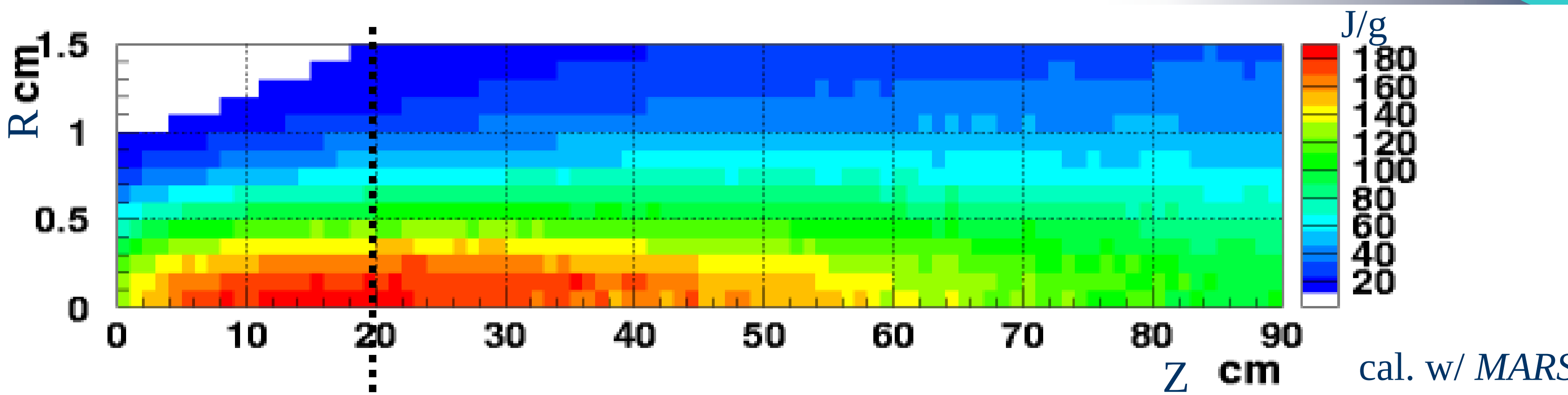
The effects of target radius

- Larger radius
  - pion yield decreases
- Smaller radius
  - Temperature increases
    - ➡ more thermal stress
  - surface area decreases
    - ➡ difficult to cool

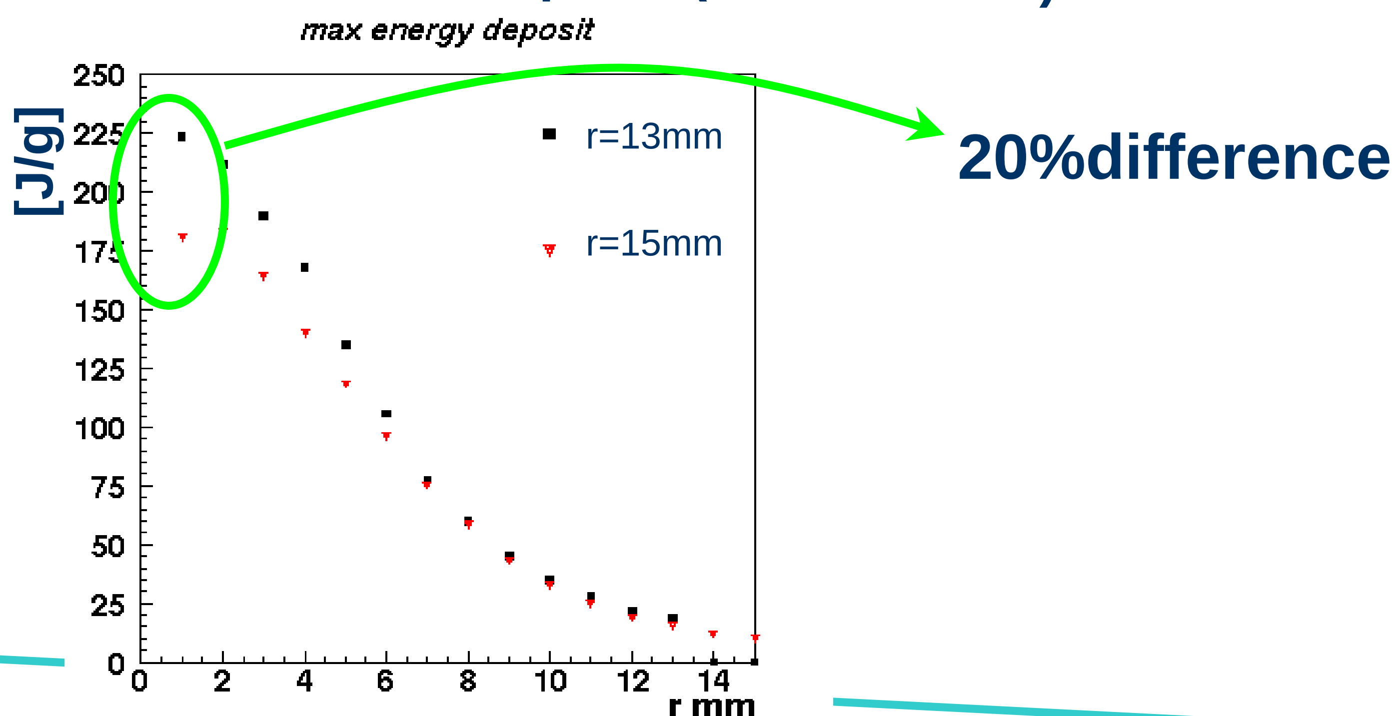
The optimization is needed



Energy deposit



heat distribution in 1pulse (15mm radius)



Thermal stress

- **Stress estimation**

quasi-static stress
(non-uniform heating)

$$\sigma_z^{stat} \approx -\frac{2}{3}\frac{E\alpha T_0}{1-\nu}$$

$$\sigma_r^{stat} \approx -\frac{E\alpha T_0}{3(1-\nu)}$$

$$\sigma_\phi^{stat} \approx -\frac{E\alpha T_0}{3(1-\nu)}$$

dynamical stress
(rapid heating)

$$\sigma_z^{dyn} \approx \pm\frac{1}{3}E\alpha T_0$$

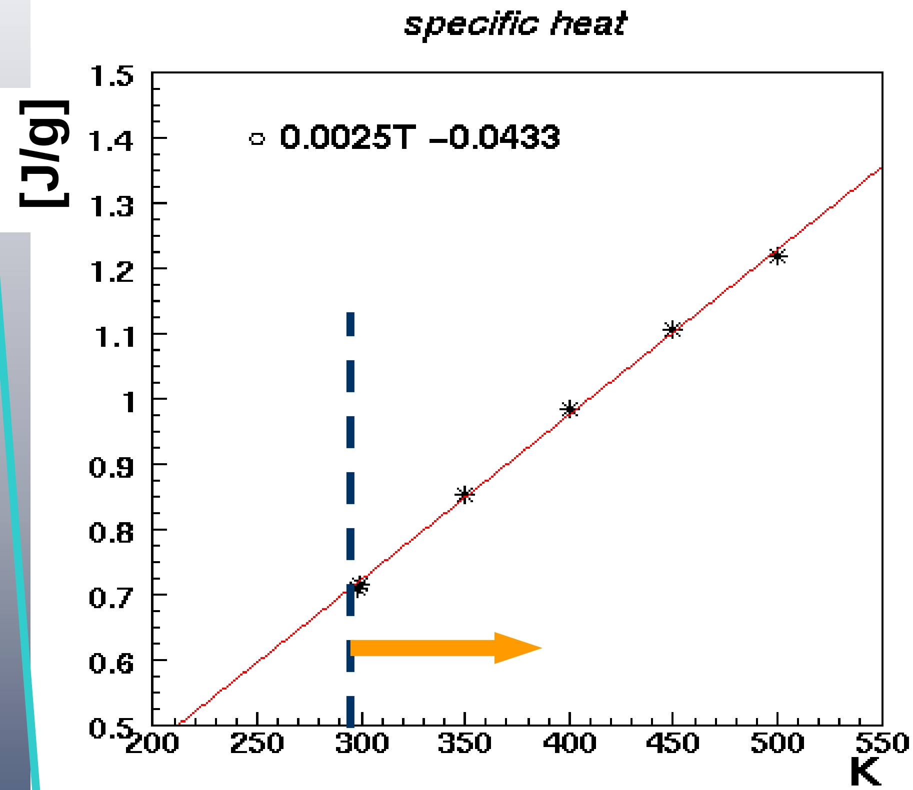
E :Young's modulus
ν :Poisson ratio
α :linear expansion coeff.
T_0:Temperature at center

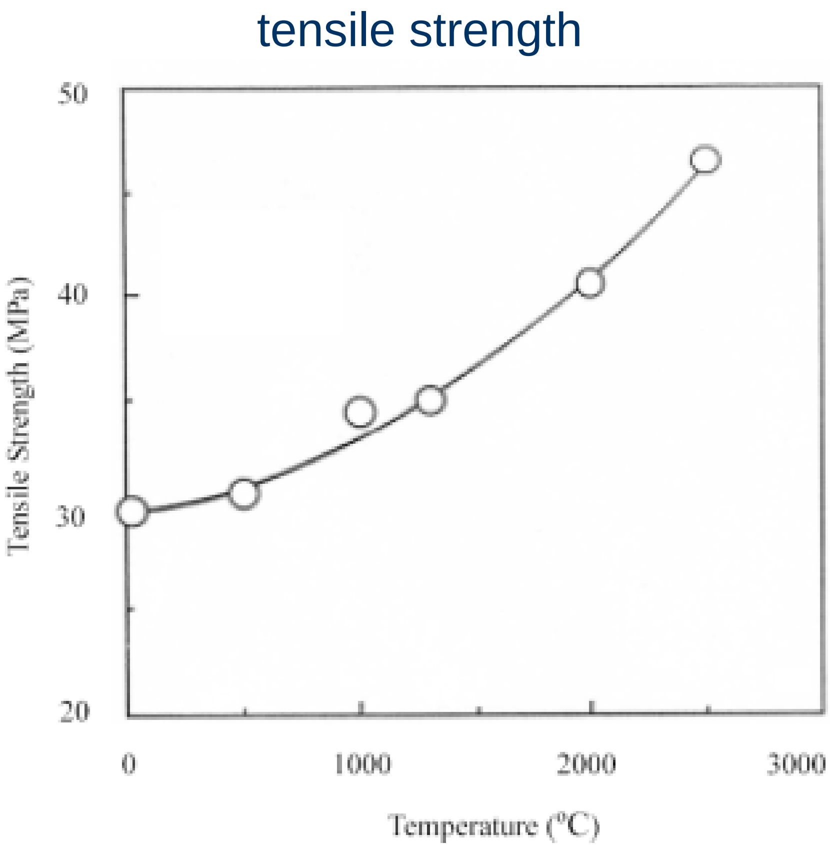
- **Material fatigue**

after repeating stress(10^6 times),
tensile strength become 0.8 (IG-110).

Material properties Ⅰ

- Temperature dependence





max temp. rise(G347)

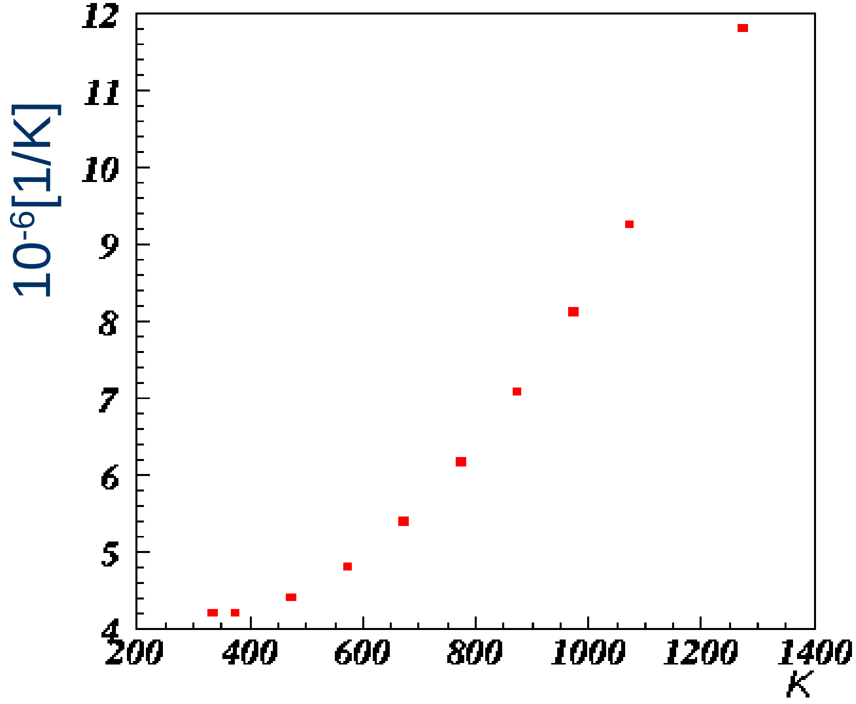
r=13mm 234.2[K]

r=15mm 200.6[K]

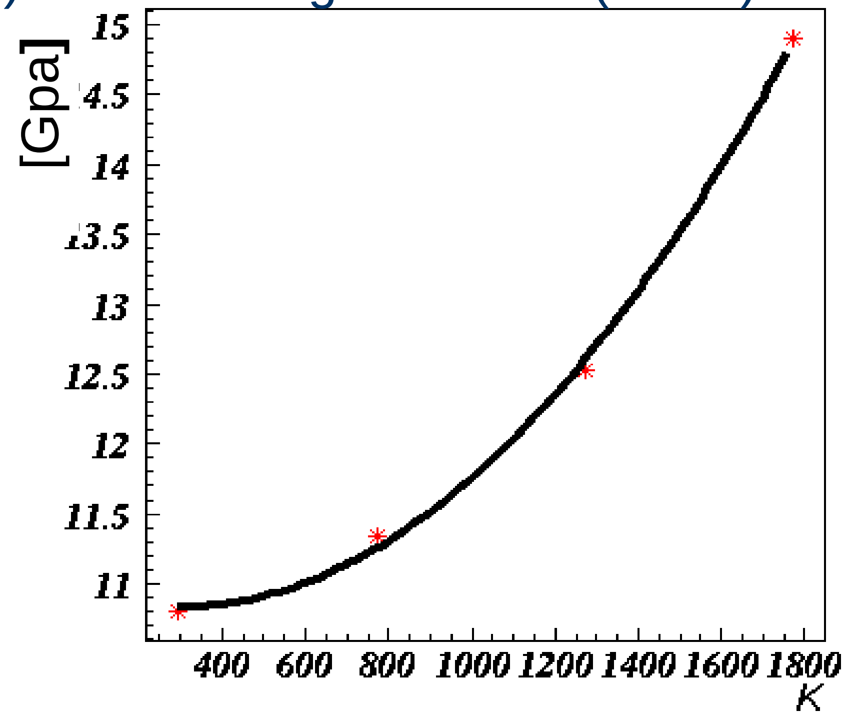
almost the same

Material properties II

thermal expansion coeff.(G347)



Young's modulus(G347)



temperature dependence exists

these effects should be taken into account.

Safety factor

- **Definition**

safety factor = (tensile strength / σ_{eq})

$$\sigma_{eq} = \sqrt{\{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2\}/2} \leq \frac{2-\nu}{3(1-\nu)} E\alpha T_0$$

- **Result** **(include fatigue、material properties)**

Type		tensile strength[Mpa]	σ_{eq} r=13[MPa]	σ_{eq} r=15[MPa]	
Toyo Tanso	IG-43	37.2→29.8	8.92(3.3)	7.48	(4.0)
Tokai Carbon	G347	31.4→25.1	6.43(3.9)	5.55	(4.5)

() is safety factor

→ These graphite have sufficient safety factor

Cooling

- **Requirement**
  - cool down 60kJ in 3.3 sec
  - keep T_{surf} under 100℃

- **α is a key parameter!**

$$Q = \alpha S(T_{surf} - T_{water}) = \alpha S \Delta T$$

$$T_{surf} = T_{water} + \Delta T$$

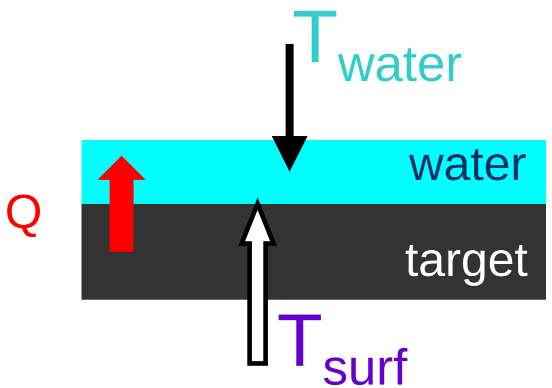
$$T_{water} \leftarrow \Delta T \leftarrow \alpha$$

Q	: heat transfer [kW]
S	: surface area [m^2]
Tsurf	: temp. at surface[K]
Twater	: temp. of water [K]
α	: heat transfer coeff. [$kW/m^2/K$]

α depends

cooling test

α **need to be measured**

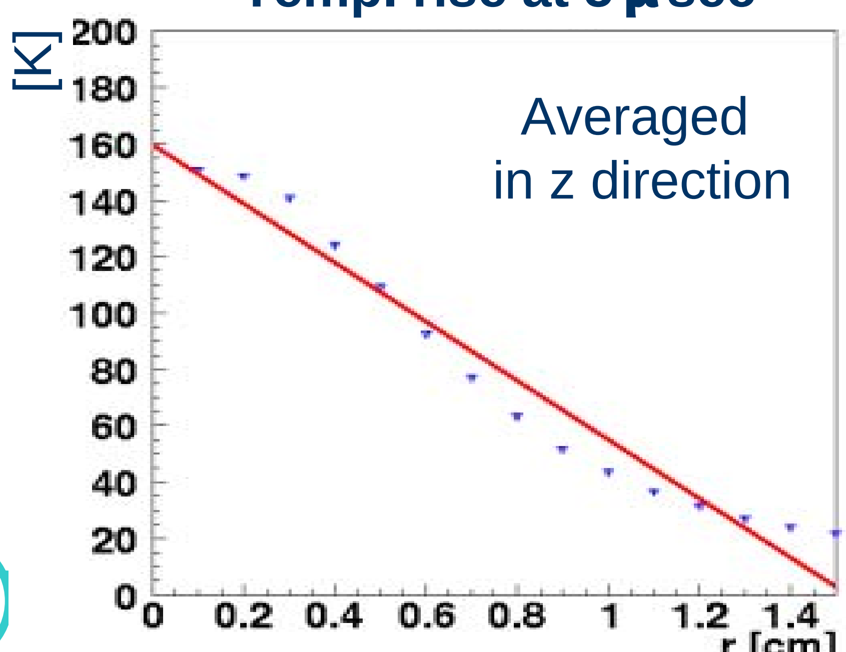


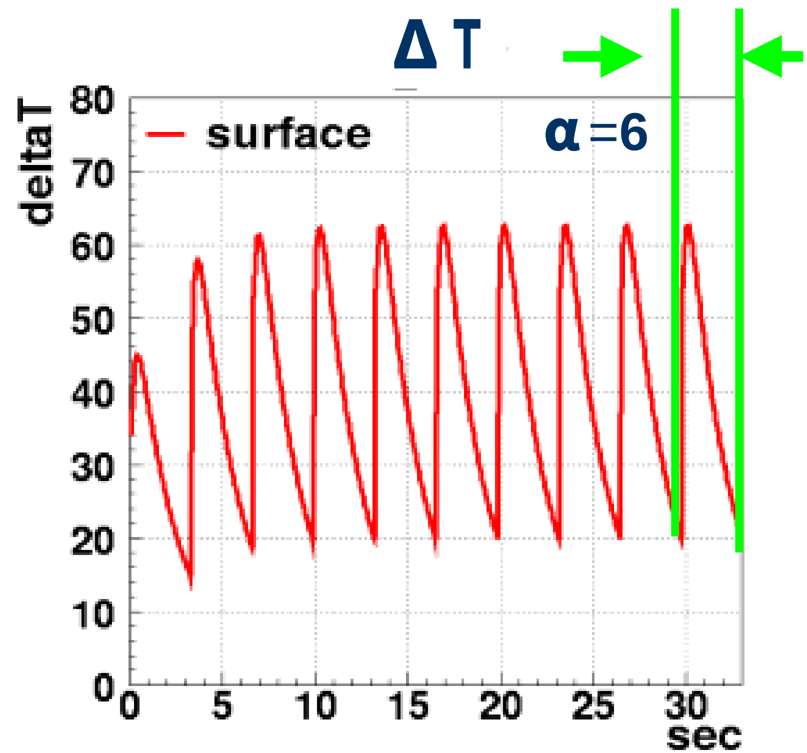
Analytical estimation of Δ T

- **Δ T(t)**

depends on
- initial condition : $T_{rise}(r)$
- heat transfer coeff : **α**

Temp. rise at 5 μ sec





Water temperature

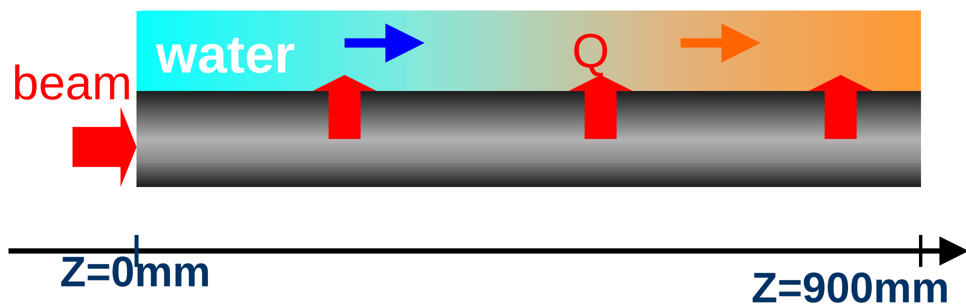
- $T_{water}(r)$ (at Z=900mm)

$T_{surf} = T_{water} + \Delta T$

to estimate maximum T_{surf} ,

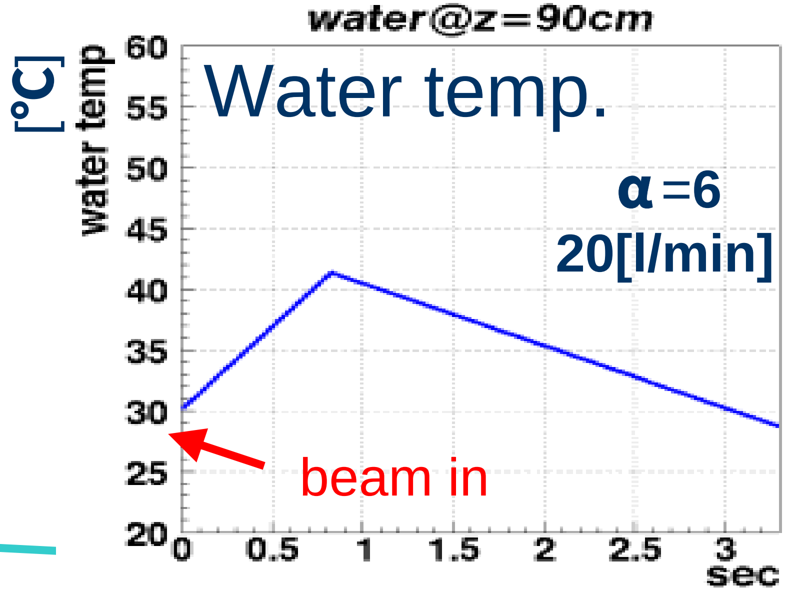
max of T_{water} is necessary

T_{water} has max at Z=900mm



heat transfer ∝ ΔT

T_{water} takes maximum value at 0.8sec



α & flow rate

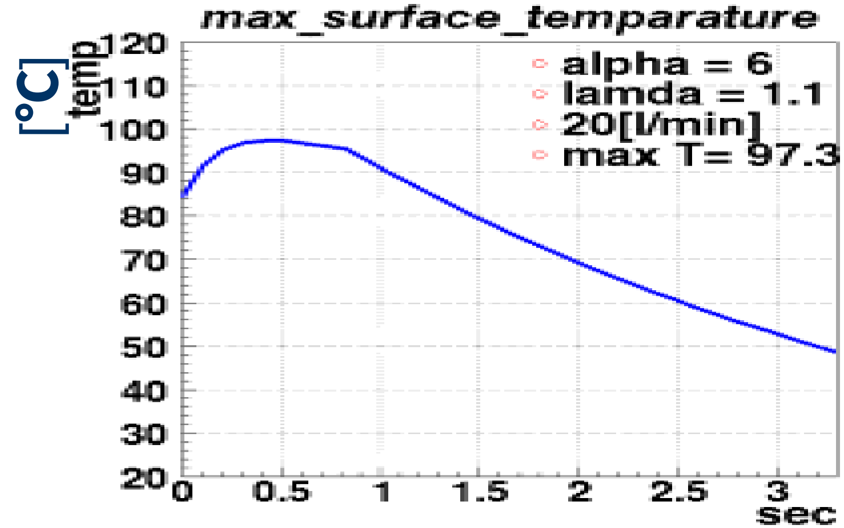
- **Calculation result**

$$T_{surf} = \Delta T + T_{water}$$

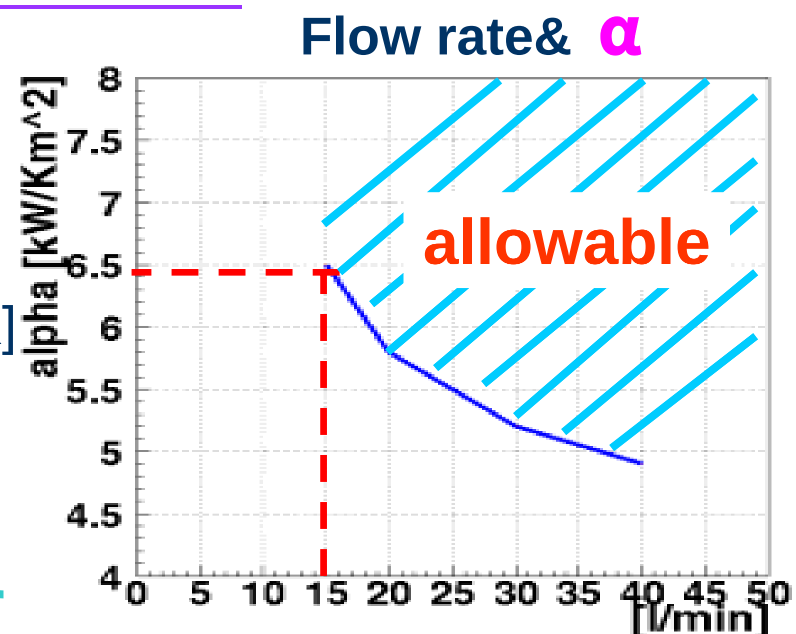
more water flow rate

➡ water temp rise : smaller

acceptable α : lower



- **Relation between α & flow rate**



satisfy T_{surf} <100℃

15[l/min] -> more than **6.5**[kW/m²/K]

20[l/min]->more than **5.8**[kW/m²/K]

Is needed

Cooling test

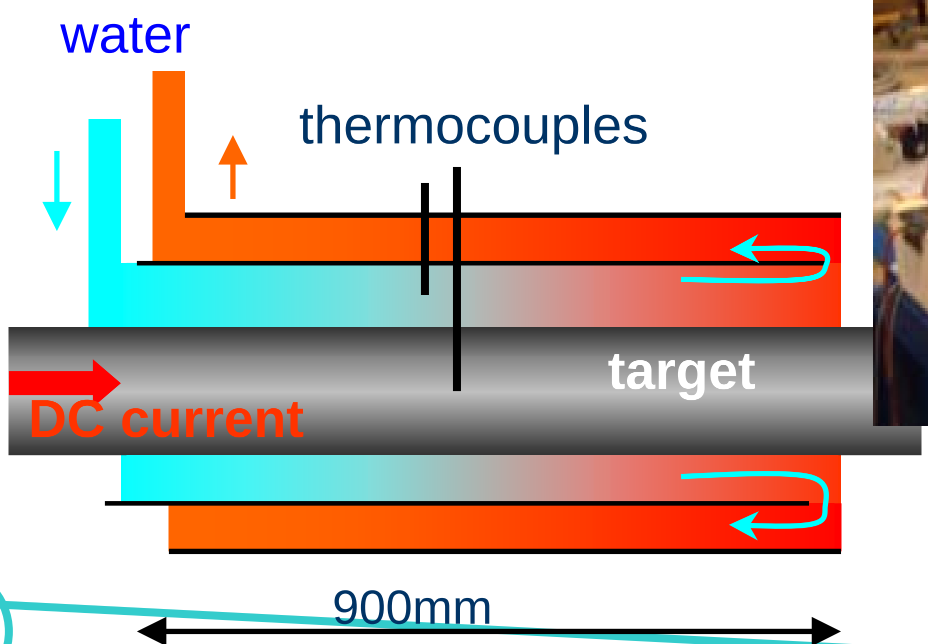
- **Purpose** measure the heat transfer coeff.
- **How** heat up the graphite with DC current , and cool by flowing water
- **Measurement** temperatures,water flow rate ,current

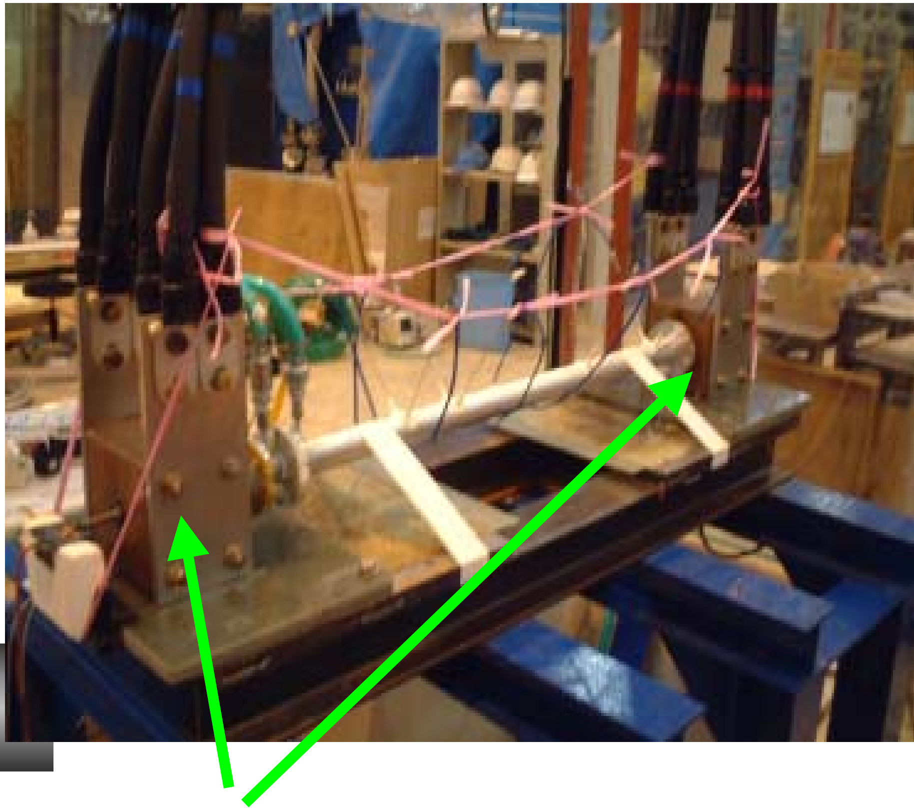
$$\alpha = \frac{Q}{S(T_{surf} - T_{water})}$$

α	: heat transfer coeff.	[kW/m²/K]
Q	:heat transfer	[W]
T_{surf}	:surface temperature	[K]
T_{water}	:water temperature	[K]
S	:surface area	[m²]

Setup of cooling test

- Current ~ 1.2kA(20kW)
- Water flow 8.9 , 12[l/min]
- Target radius 15mm



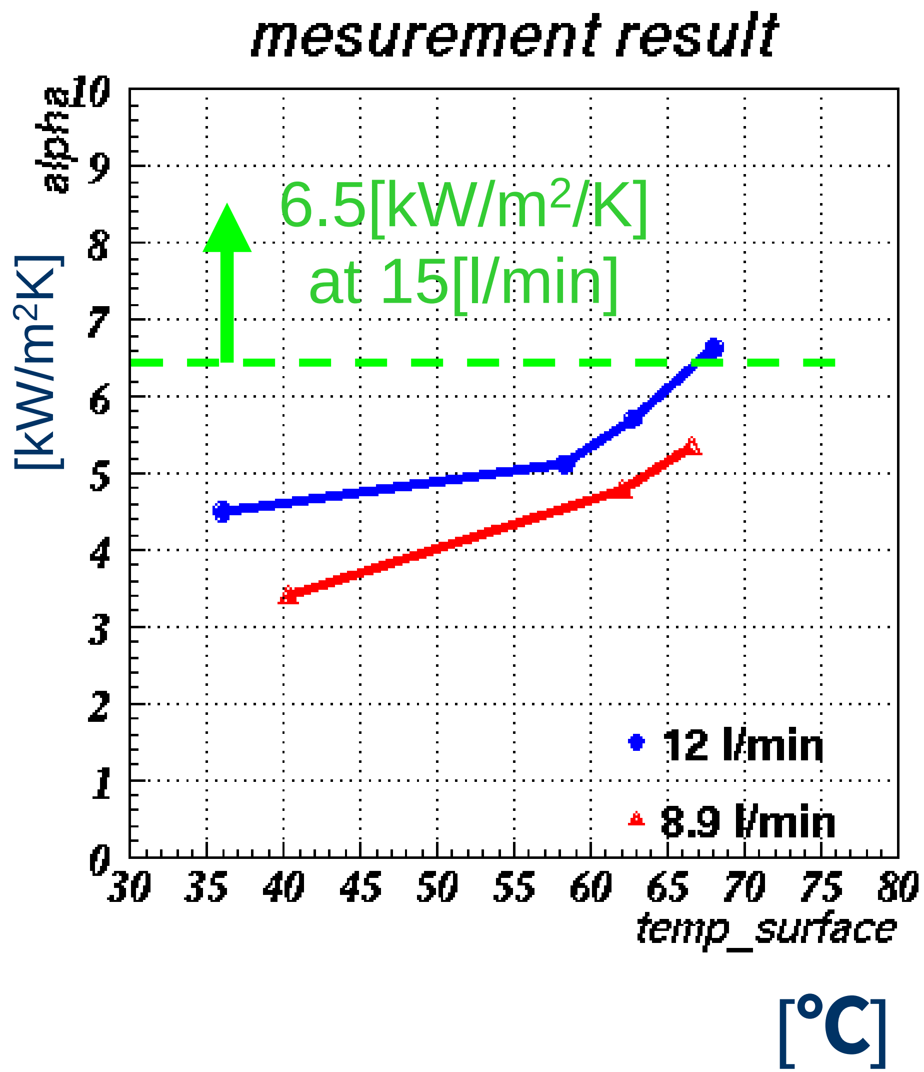


Cooling test results

α increase with
surface temperature
& water flow rate

compared with
the α condition

extrapolate with
theoretical formula



Comparison w/ theoretical formula

Theoretical formula

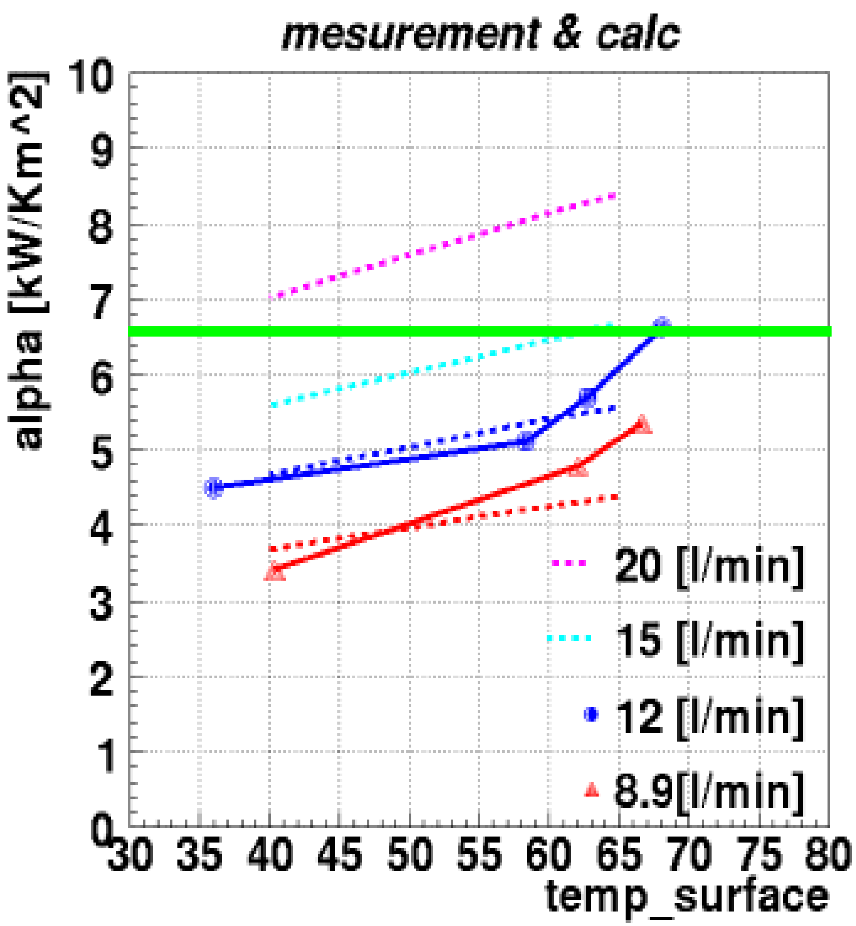
$$\alpha = \frac{0.023 \times \mathrm{Re}^{0.8} \times \mathrm{Pr}^{0.4} \times \lambda}{d}$$

Re(T) :Reynolds number

Pr(T) :Prandtl number

λ(T) :Thermal conductivity

d :equivalent diameter



Result

Data and calculation seems to agree

at 20 [l/min] ,

α expected to satisfies the condition !

Summary

- **Thermal stress**

		max stress	safety factor
r=15mm	IG-43	7.48[MPa]	4.0
	G347	5.55[MPa]	4.5

- **cooling calc.** relations between α & flow rate

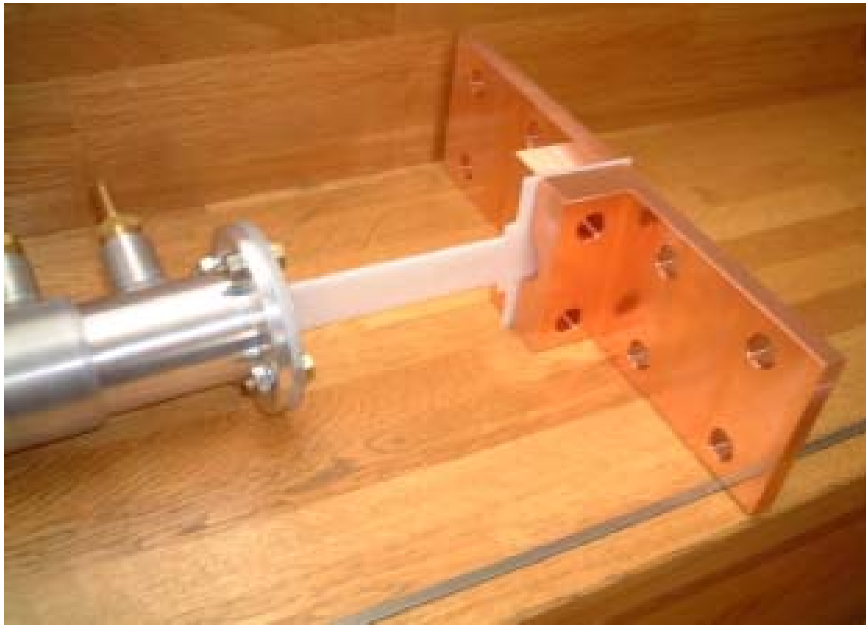
  r=15mm 15[l/min] ,6.5[kW/m^2/K]

  20[l/min] ,5.8[kW/m^2/K]

- **cooling test** possible to cool at more than 20[l/min]

Schedule

- Next cooling test with more flow rate



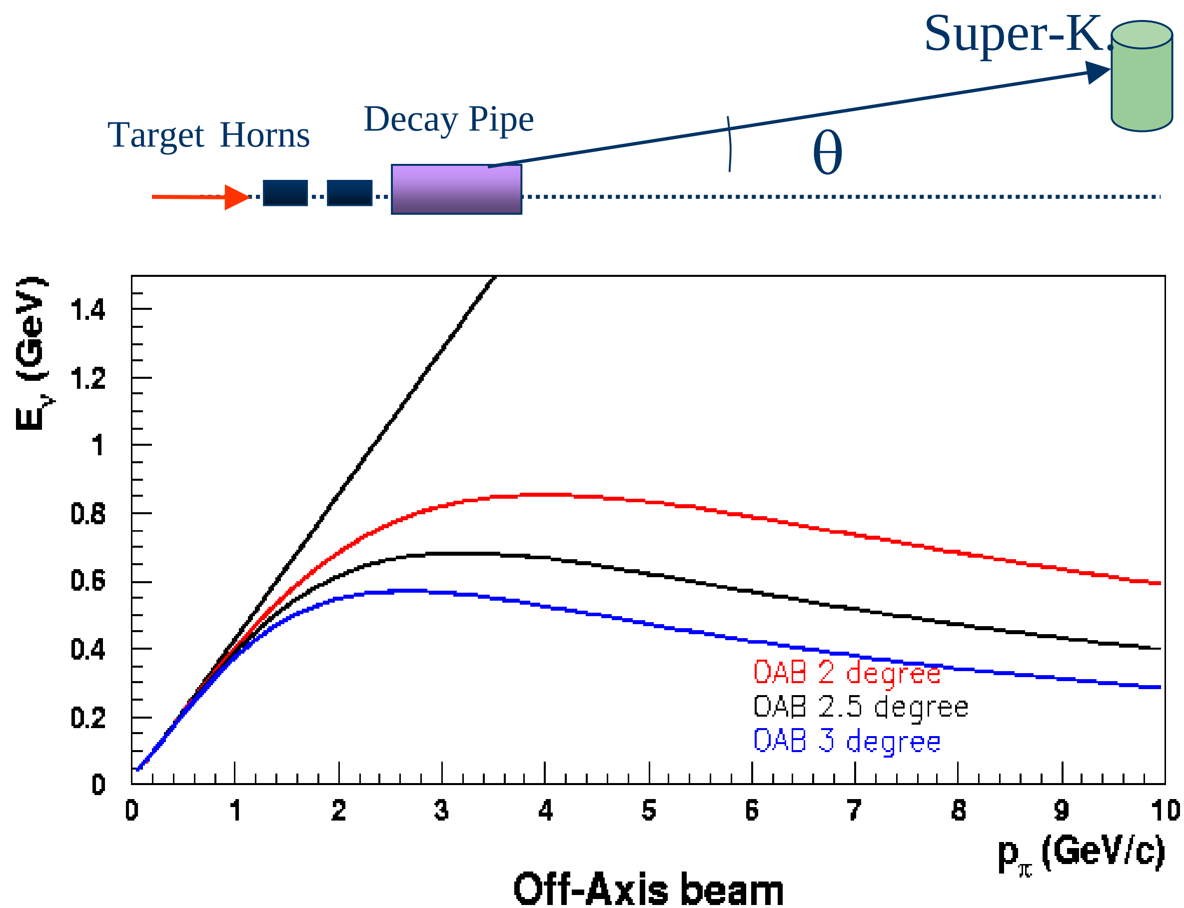
We plan to test with 20 [l/min] this month

reference1

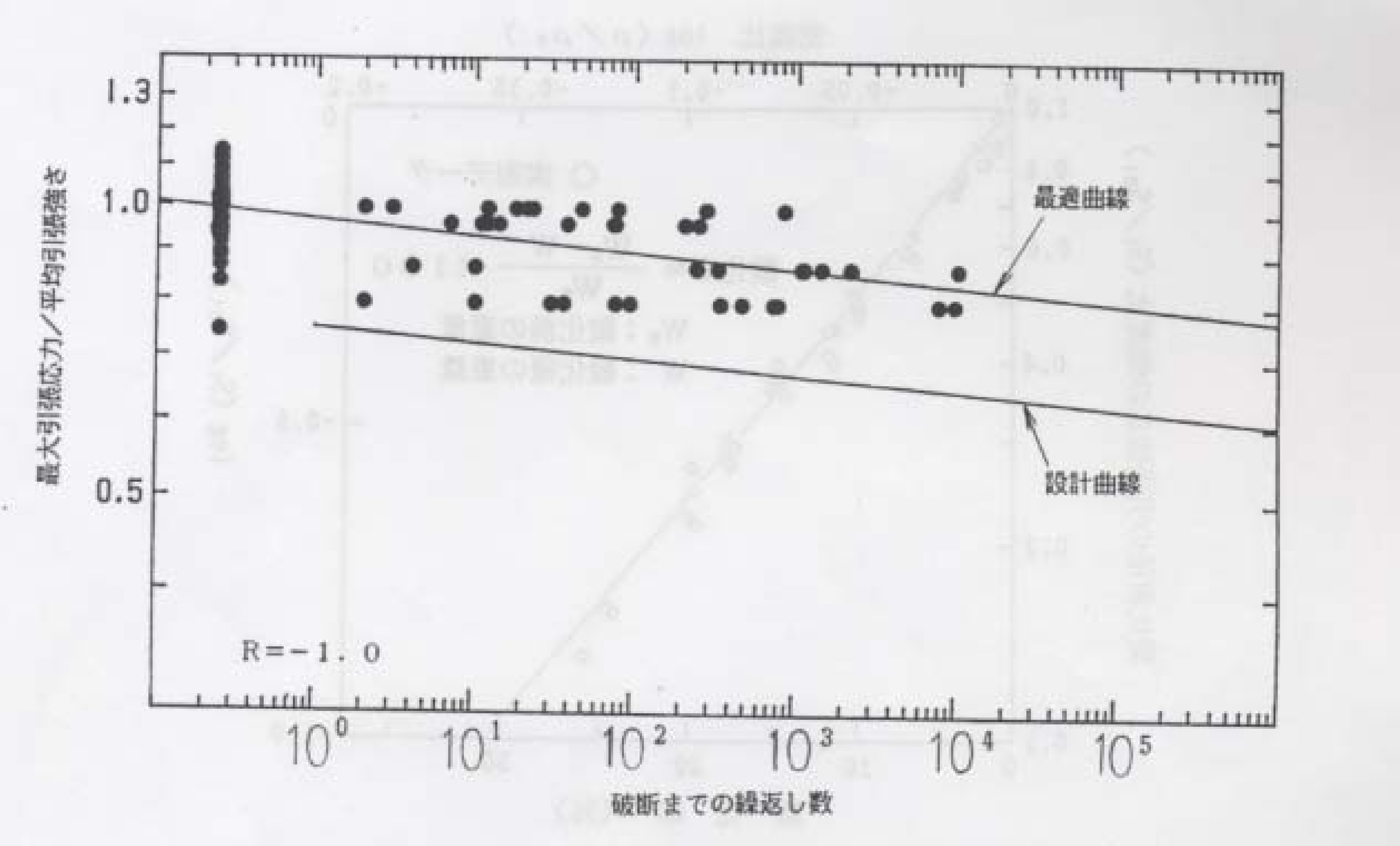
- off-axis-beam

  ⇒high intensity

  narrow energy band



reference2



最大引張応力／平均引張強さ
1.3
1.0
0.5
最適曲線
設計曲線
R=−1.0
10^0
10^1
10^2
10^3
10^4
10^5
破断までの繰返し数

reference 3

- $\sigma_z^{stat}, \sigma_r^{stat}, \sigma_\phi^{stat}, \sigma_z^{dyn}$

$$\sigma_z^{stat} = \frac{\alpha E}{1-\nu}\left(\frac{2}{R^2}\int_0^R rT(r)dr - T(r)\right)$$

$$\sigma_r^{stat} = \frac{E\alpha}{1-\nu}\left(\frac{1}{R^2}\int_0^R rT(r)dr - \frac{1}{r^2}\int_0^r rT(r)dr\right)$$

$$\sigma_\phi^{stat} = \frac{E\alpha}{1-\nu}\left(\frac{1}{R^2}\int_0^R rT(r)dr + \frac{1}{r^2}\int_0^r rT(r)dr - T(r)\right)$$

$$\sigma_z^{dyn} = \pm E\alpha\frac{2}{R^2}\int_0^R rT(r)dr$$

$$\sigma_{eq} = \sqrt{\left\{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2\right\}/2} \leq \frac{2-\nu}{3(1-\nu)}E\alpha T_0$$

reference 4

ΔT(r) time development

When the target surface is cooled (at r=R)with **α**,
temperature difference between Tsurf and Twater
(at r,time=**τ**) : $\Delta T(r,\tau)$ is, $T_0(r)$

$$\begin{cases} T(r,0) = ur + v \\ \dfrac{\partial T}{\partial \tau} = a\left(\dfrac{\partial^2 T}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial T}{\partial r}\right) \\ \left(\dfrac{\partial T}{\partial r}\right)_{r=R} = -\dfrac{\alpha}{\lambda} T_{r=R} \end{cases}$$

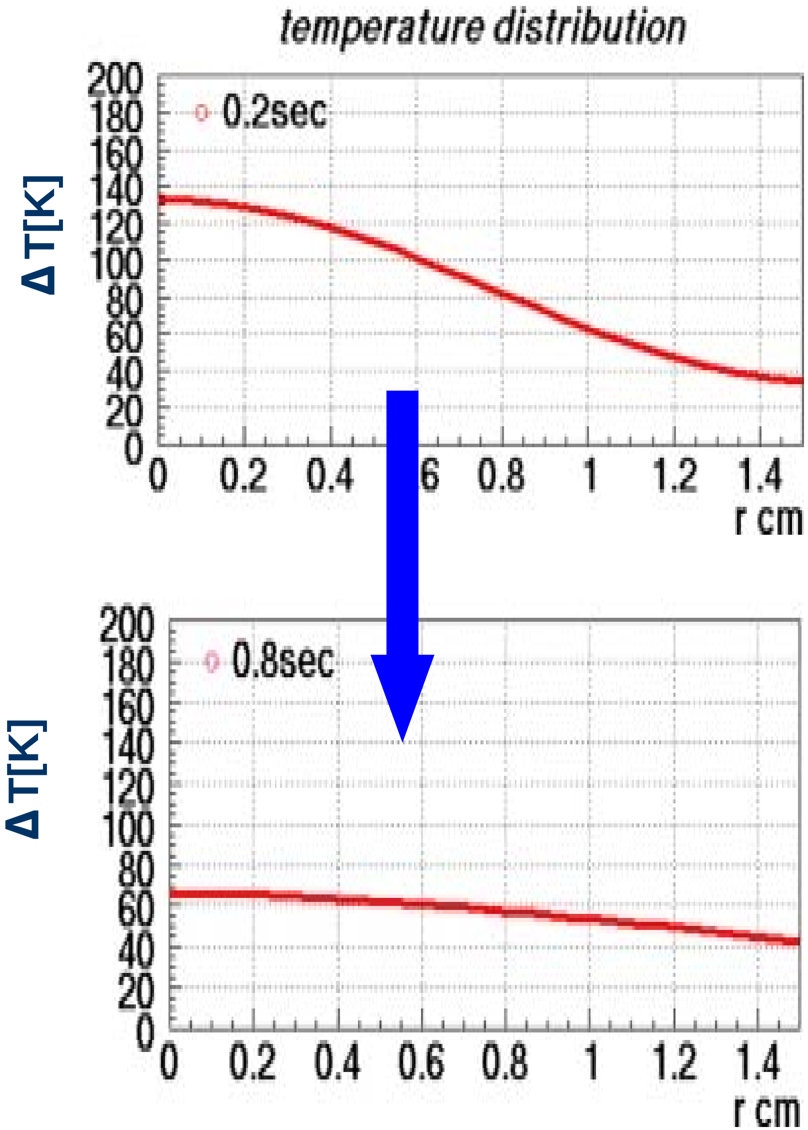
λ:heat conductivity
a:thermal diffusivity

$$\Delta T(r,\tau) = \sum_{n=1}^{\infty} \frac{2\int_0^R T_0(r) r J_0(q_n r)dr}{R^2\{J_0(q_n R) + J_1(q_n R)\}} e^{-q_n^2 a\tau} J_0(q_n r)$$

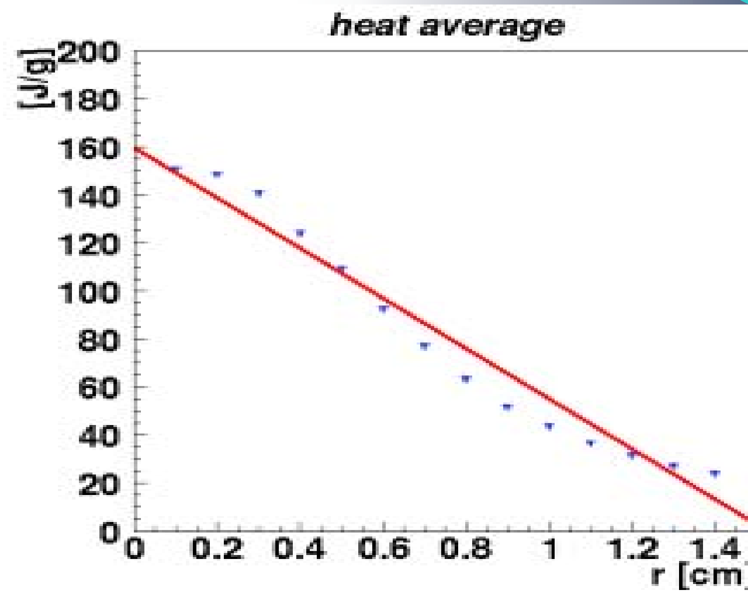
ただし

$$q_n R J_1(q_n R) = \frac{\alpha R}{\lambda} J_0(q_n R) (n = 1,2,\cdots)$$

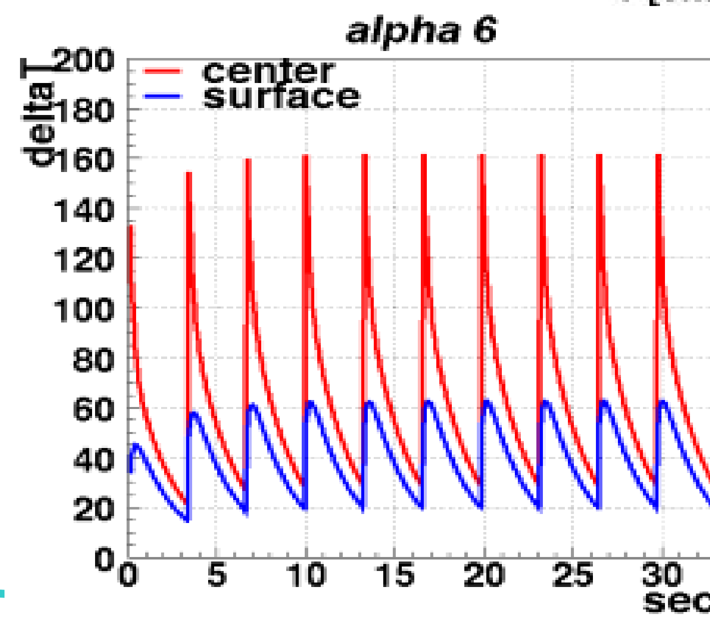
reference 5



temperature distribution
ΔT[K]
0.2sec
r cm
ΔT[K]
0.8sec
r cm

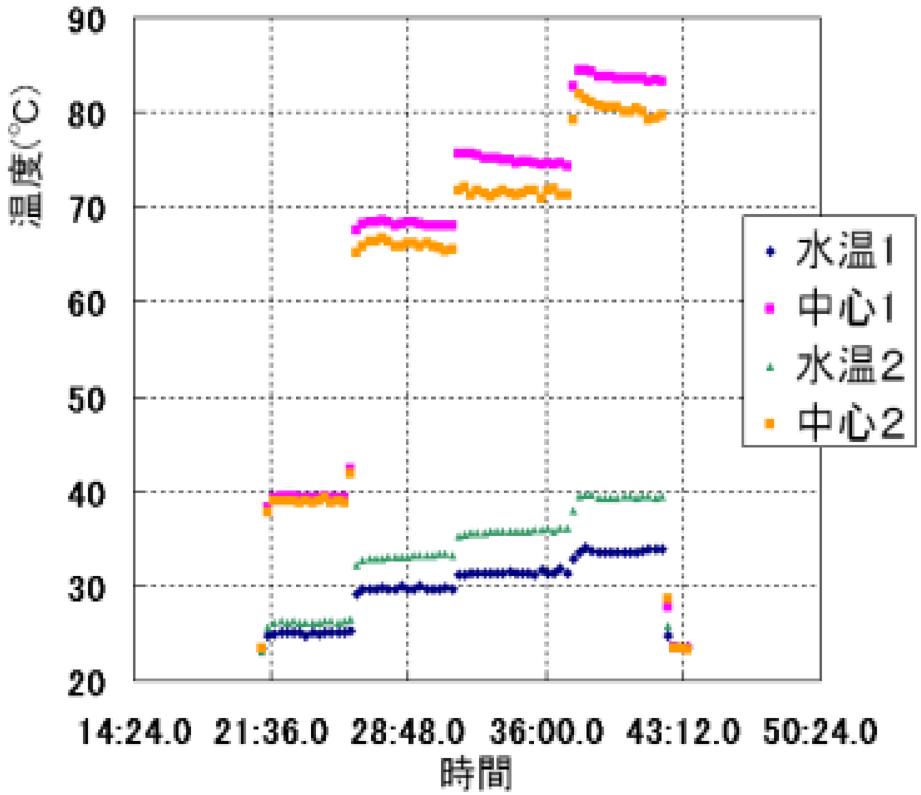


heat average
[J/g]
r [cm]

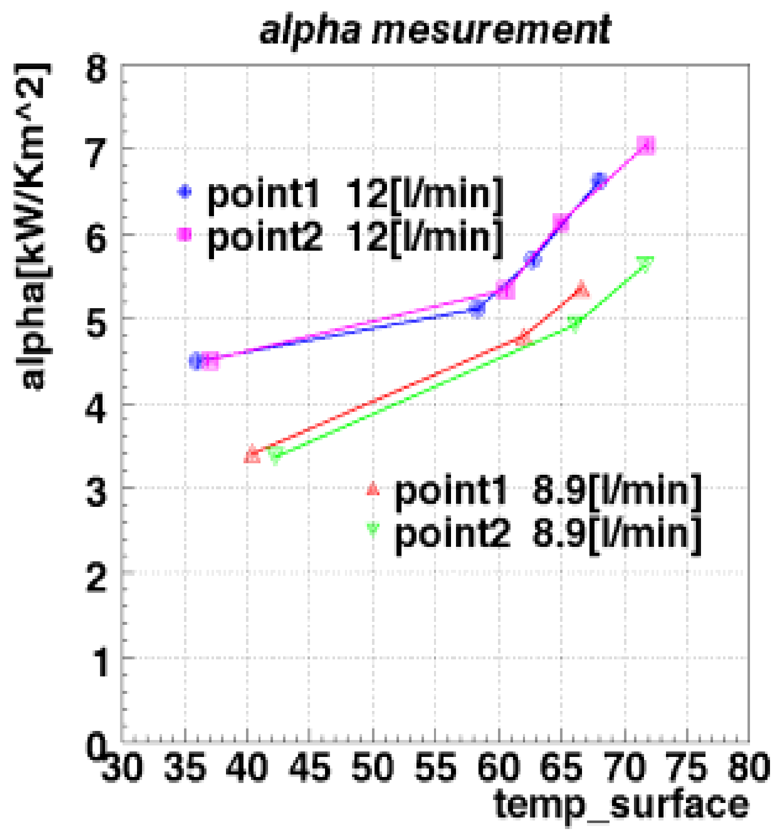


alpha 6
delta T
center
surface
sec

reference6



温度(℃)
90
80
70
60
50
40
30
20
14:24.0 21:36.0 28:48.0 36:00.0 43:12.0 50:24.0
時間
水温1
中心1
水温2
中心2

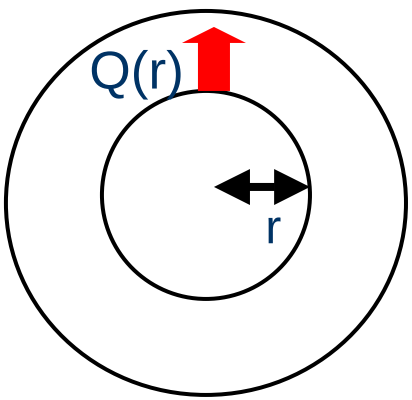


alpha mesurement
alpha[kW/Km^2]
point1 12[l/min]
point2 12[l/min]
point1 8.9[l/min]
point2 8.9[l/min]
0 1 2 3 4 5 6 7 8
30 35 40 45 50 55 60 65 70 75 80
temp_surface

参考6

■ **熱量と中心温度から表面温度**

長さ方向に熱の移動がないと仮定した場合、
ターゲット内部では一様発熱。



$$Q(r) = -2\pi r c \lambda \frac{dT}{dr} = \pi r^2 q$$

$$\lambda = Ae^{-aT}$$

$$T_{surf} = -\frac{1}{a}\ln\left(\frac{aqR^2}{4A} + e^{-aT_{center}}\right)$$

λ：熱伝導度
c：**比熱**
q：**単位体積当たりの発熱量**
R：**半径**

冷却試験

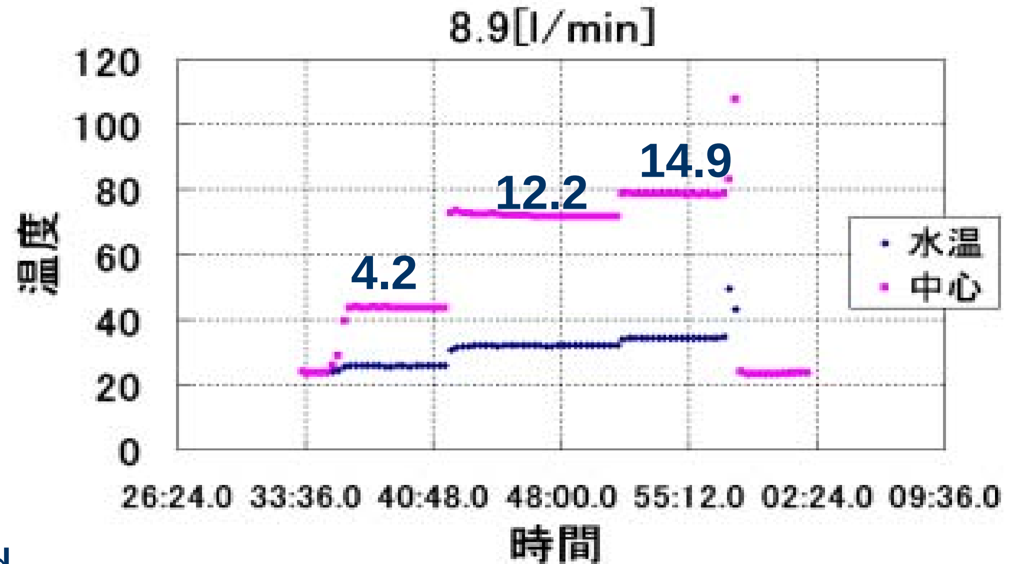
- **data**

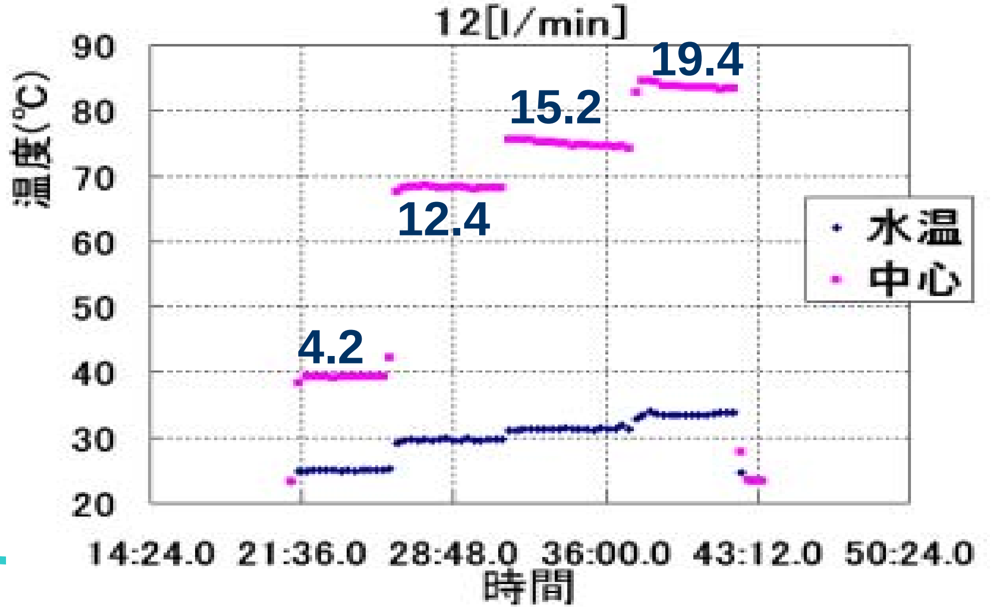
$$\alpha = \frac{Q}{S\,(T_{surf} - T_{water})}$$

POWER :4.2kW~19.4kW

flow rate :8.9 ,12[l/min]

each data points are averaged





JPARC neutrino beamline

Proton beam kinetic energy
50GeV (40GeV@T=0)

# of protons / pulse
3.3×10^{14}

Beam power
750kW

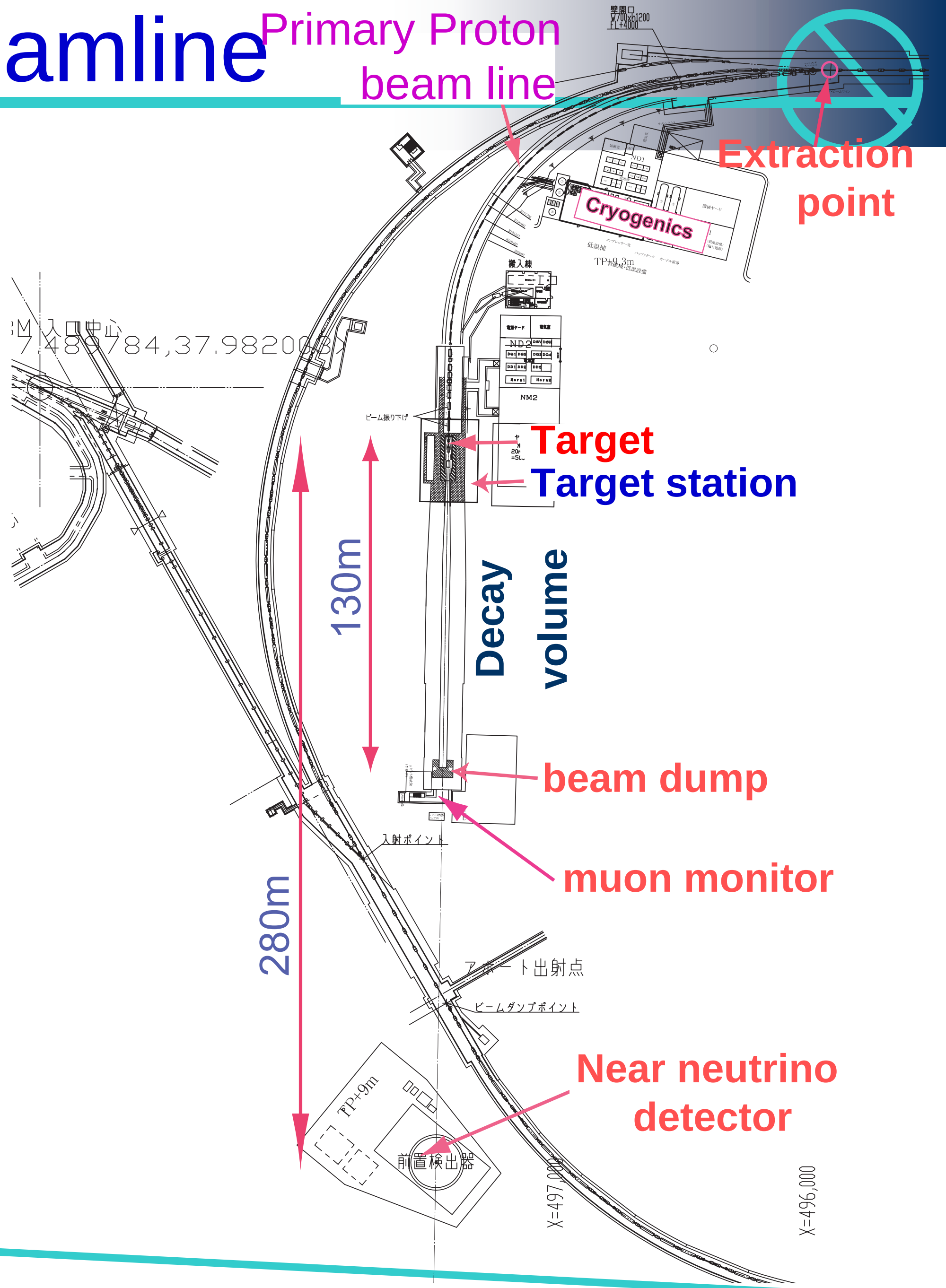
Bunch structure
8 bunches

Bunch length (full width)
58ns

Bunch spacing
598ns

Spill width
~5μs

Cycle
3.53sec



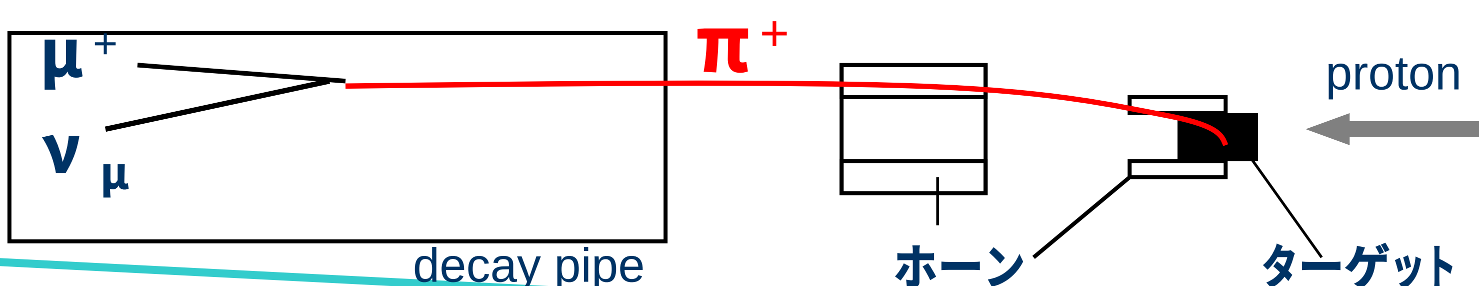
J-PARC ニュートリノ 実験

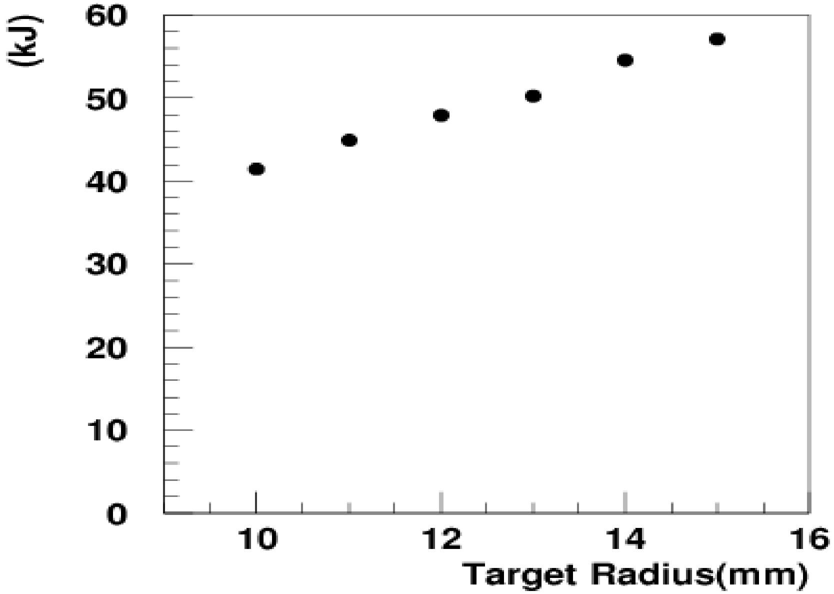
目的

- $\nu_\mu \rightarrow \nu_e$
- ν_μ disappearance
- CPV in lepton sector

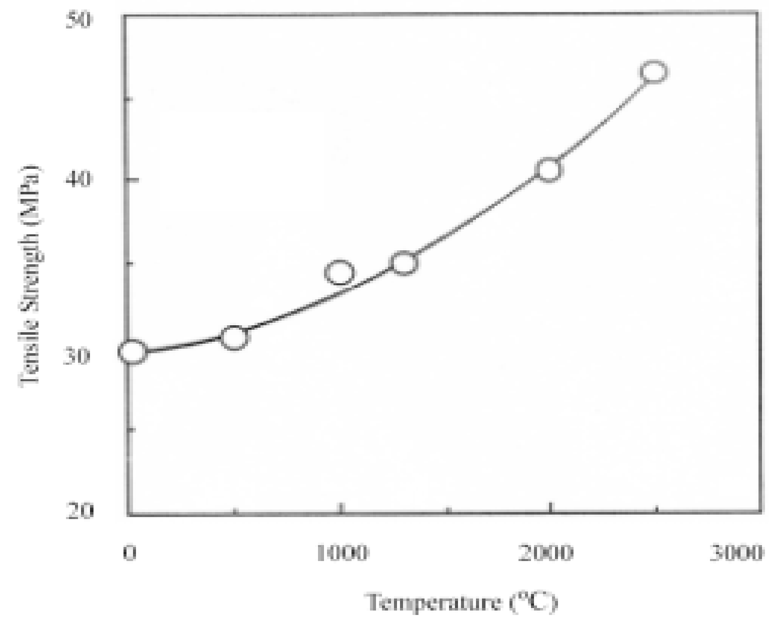
➡ **十分な統計が必要**

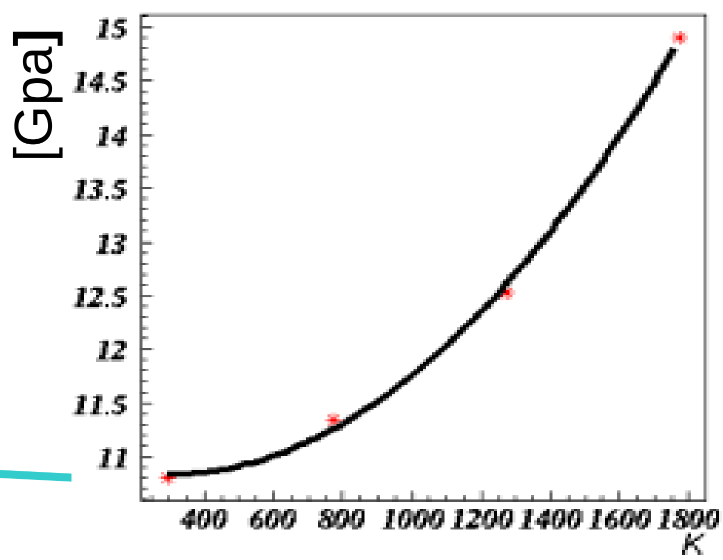
	J-PARC	K2K
Energy (GeV)	50	12
Int. (10^{12}ppp)	330	6
beam間隔(sec)	3.3	2.2
Power (kW)	750	5.2



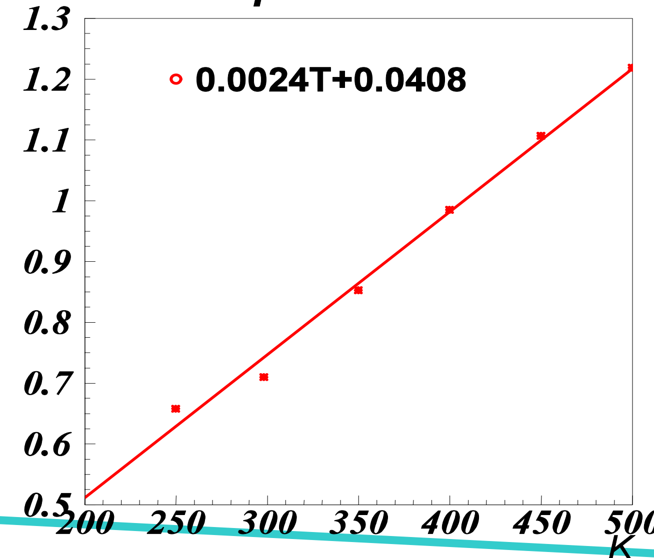


Total Energy Deposit

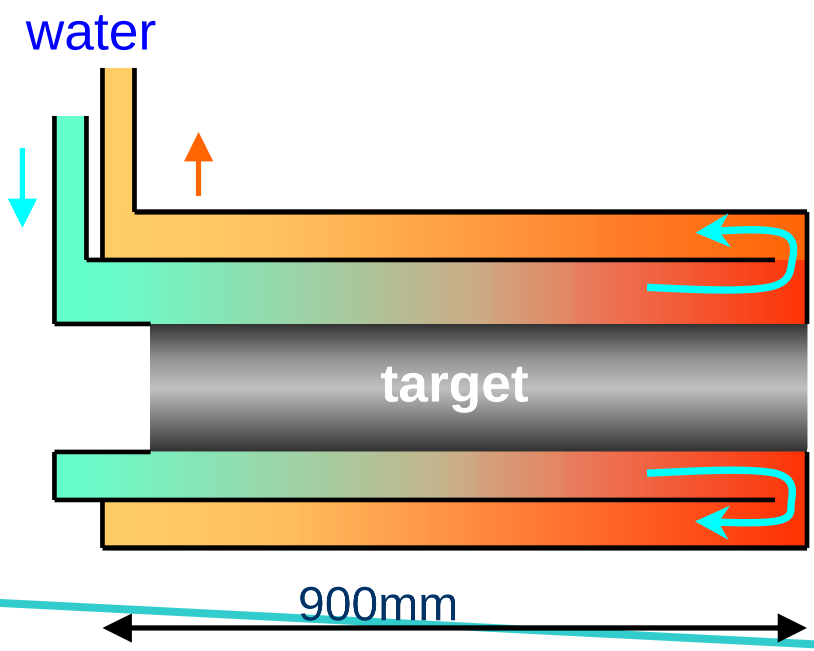




specific heat

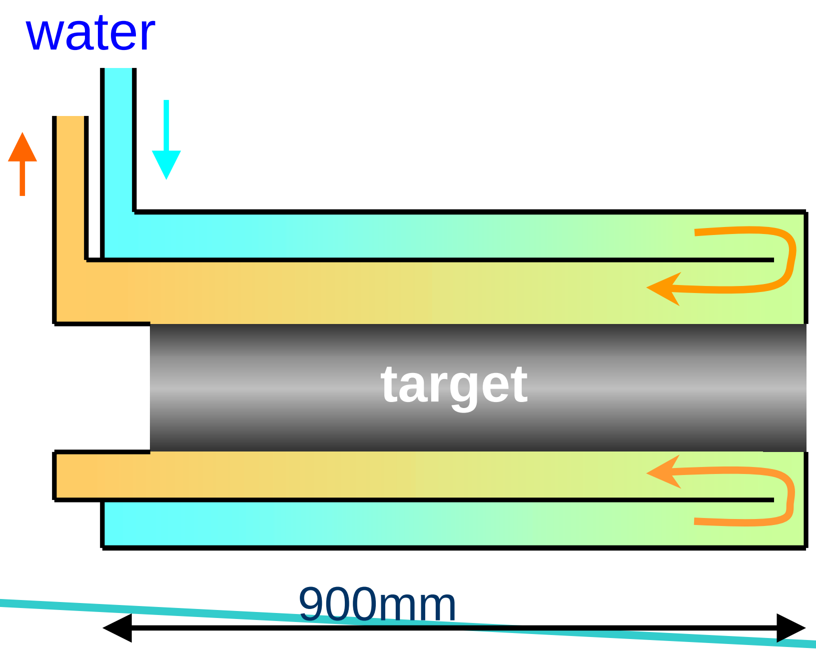


Water flow 1



Water flow 2

- s



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