# High Power Issues: status and simulation

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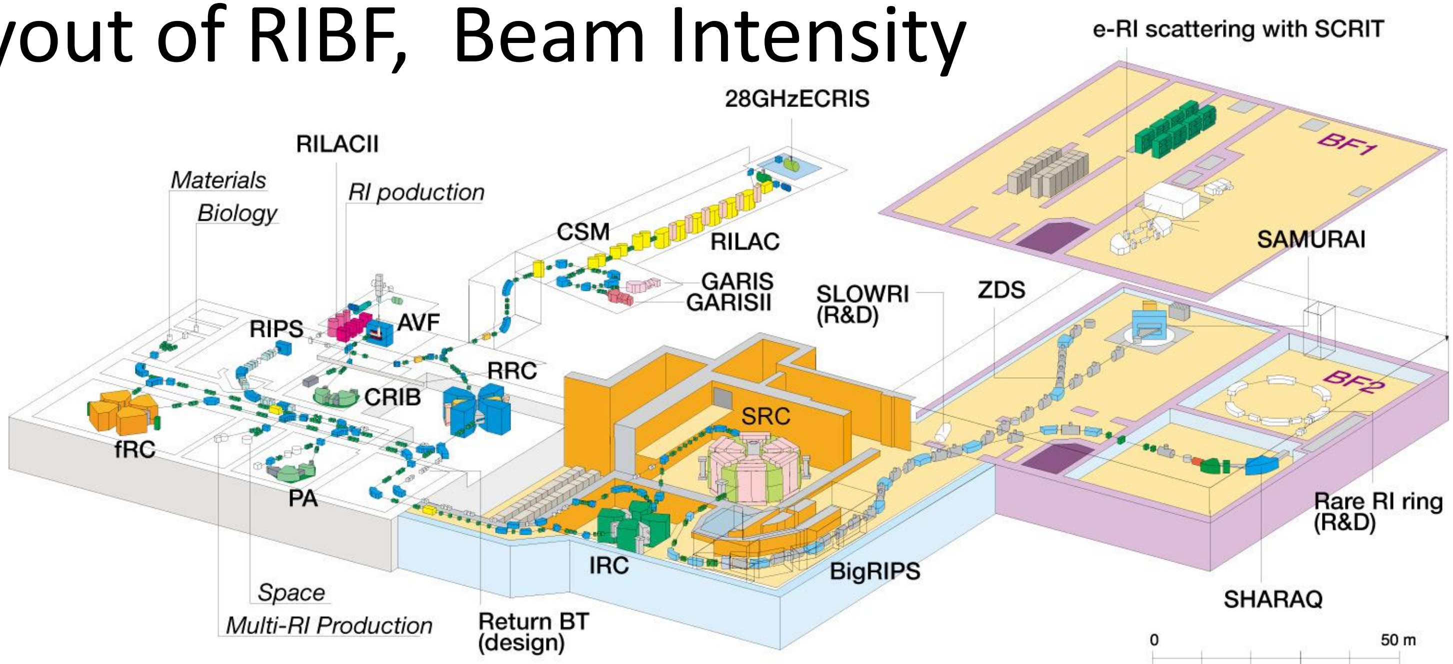
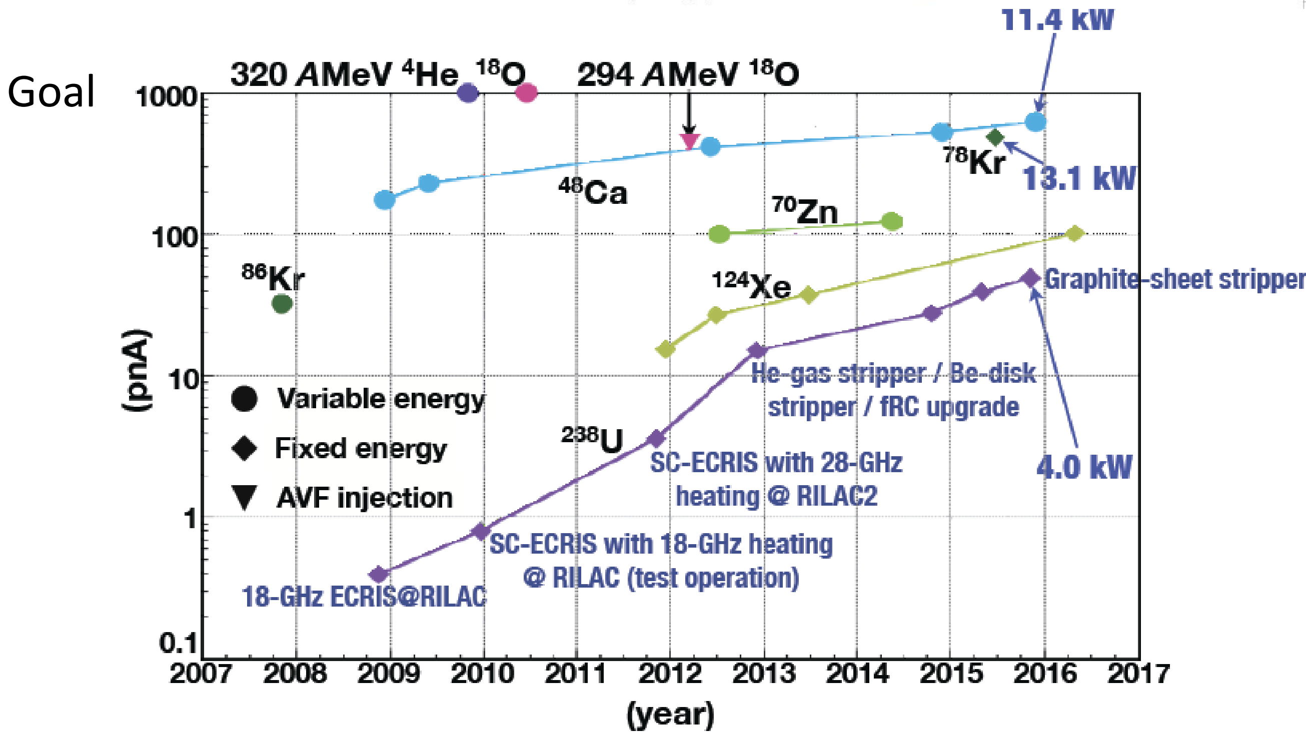
6th Expert Meeting, Grand Rapids, MI

Aug. 30 – Sep. 1, 2016

# Layout of RIBF, Beam Intensity




- Operation of RIBF started in 2007.
- Maximum energy is ~350MeV/n for heavy ions up to $^{238}U$
- Goal intensity is 1 pμA for all ions.
- Beam intensities increase year by year.
- 1/6 of Goal beam power (82kW) is achieved.

# Critical high beam-power issues of BigRIPS

High Power Production Target------ temperature measurement
High Power Beam Dump ------ temperature measurement
Protection from radiation
- energy deposit and heating
- radiation damage
- activation
- shielding
  - equipments
  - facility
- safety operation
  - fast-interlock
  - beam loss monitor (primary beam line)

Maintenance scenario and remote handling
- pillow seal system
- target maintenance system
- maintenance scenario of beam dump, STQ, Dipole, valve box , …
- cooling water system

Radiation transportation calculation (PHITS calculation)
- Full calculation along the BigRIPS beam line
- Comparison with experimental data

Cooling water issue (target and beam dump)
- activation
- erosion/corrosion
- dissolved oxygen

Liq. He system
- Heat load
- activation of He (tritium)

Today's talk:
1) recently installed devices
   - fast-interlock system
   - radiation heat load compensator for STQ1
2) Target & Beam Dump
   - evaluation of cooling capacity
   - temperature measurements and ANSYS simulation

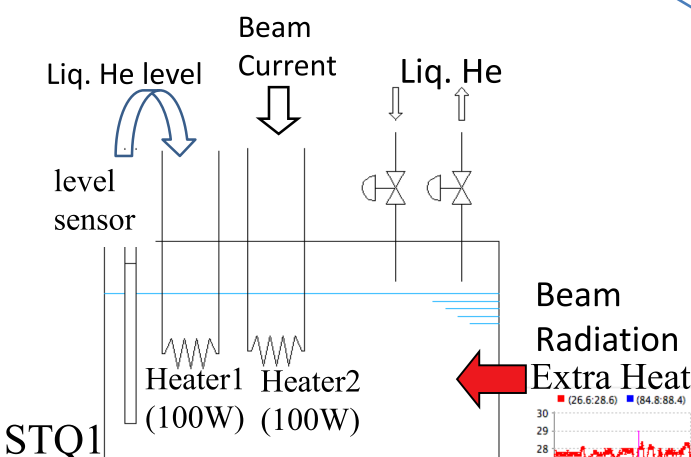
# Recent improvement of BigRIPS

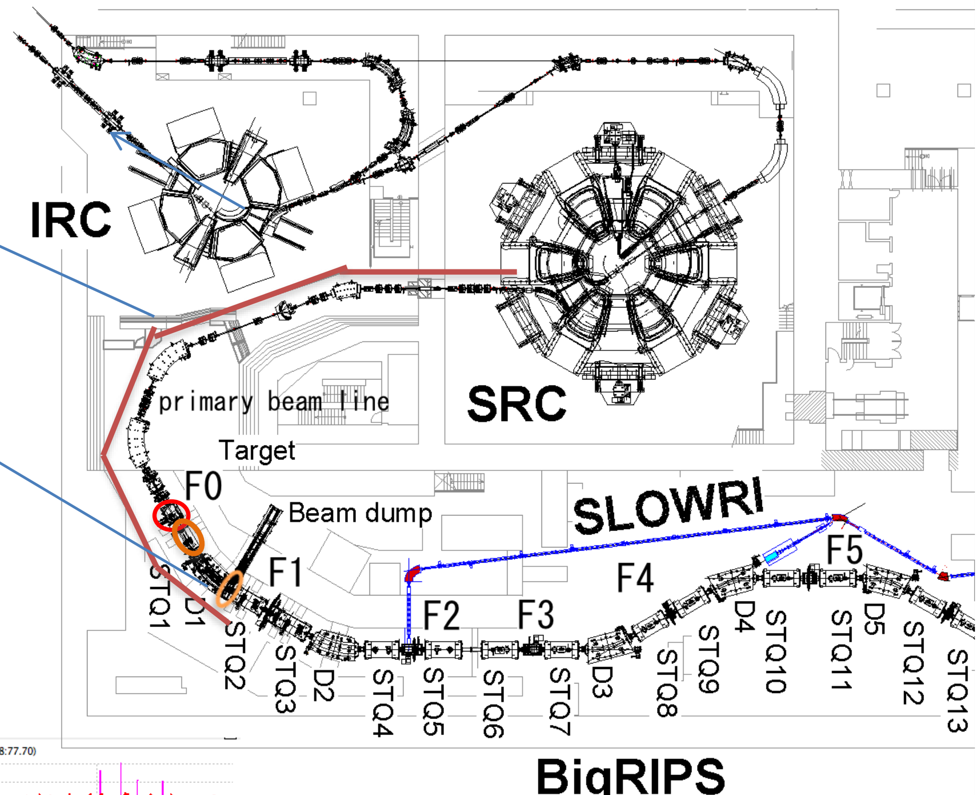
---Tolerance for high power beams up to $^{48}$Ca 345MeV/n 1pμA (final goal: $^{238}$U 1pμA) ---

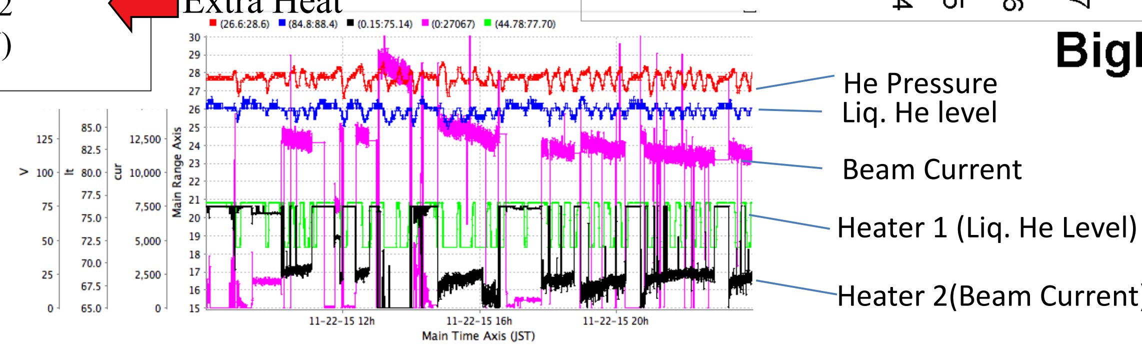
1) Fast Interlocking system
   - Drift of currents of Magnets (primary beam line)
     1% drift for Q-Mag., 0.3% drift for D-Mag.

   Fail signal is connected to beam chopper system at the exit of ion source. ~200μs response
   - Target Temperature ~300μs response

2) Radiation heat load compensator
   (heater in liq. He at STQ1)



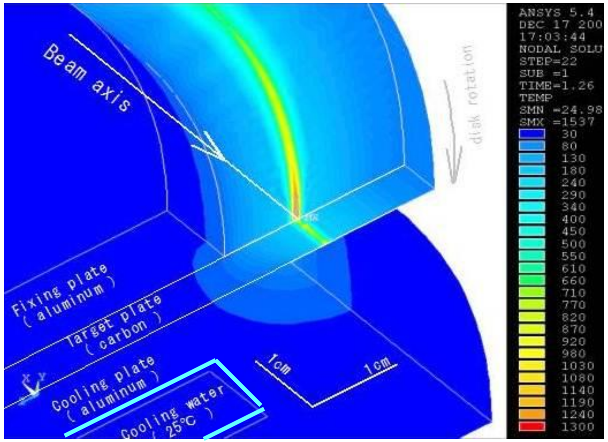



# BigRIPS Target system

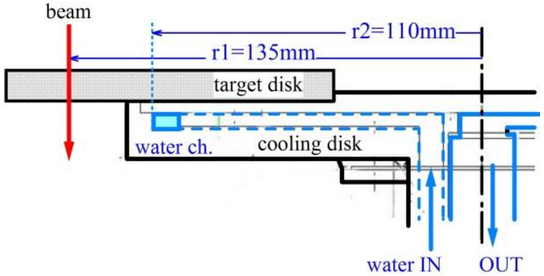
Designed and built by Dr. Atsushi Yoshida,
Toshiyuki Kubo, 2002 – 2006

Nucl. Instr. Meth. A521(2004)65
Nucl. Instr. Meth. A590(2008)204
Nucl. Instr. Meth. A655(2011)10

ANSYS (FEM code) simulation




T(water ch.)=25C




Sustainable for a $^{238}$U beam at 345 MeV/n, 1pμA

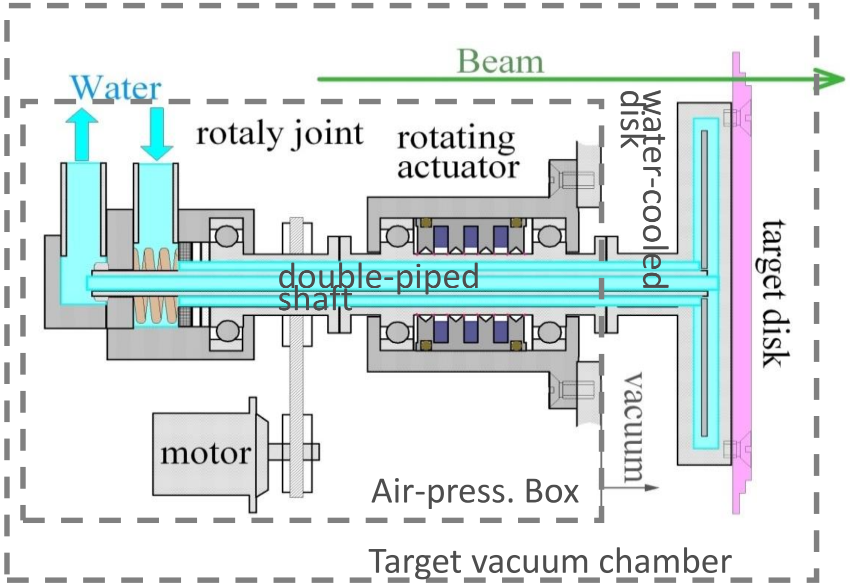
Heat Load for 4mm Be target: 17.8 kW

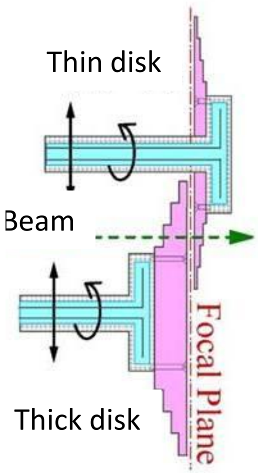
ϕ1 mm beam spot : 22.7 kW/mm$^2$

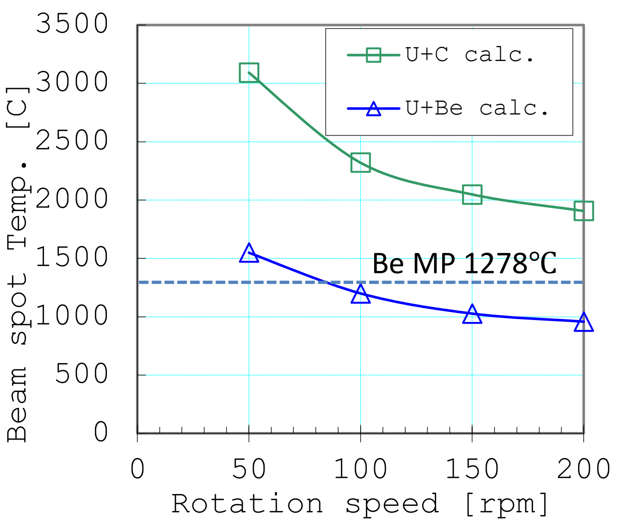
5.67 kW/mm$^3$

ANSYS Simulation -> ϕ 300 mm rotating disk with water cooling

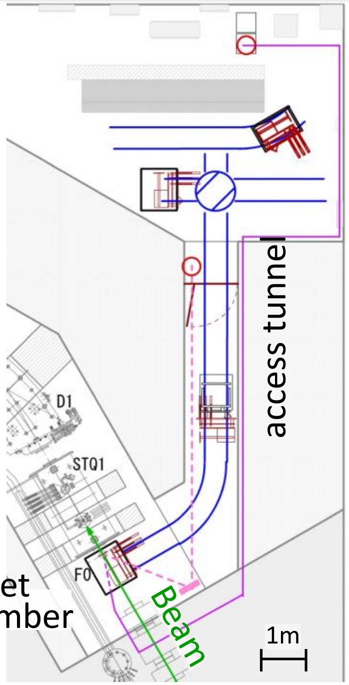
Step-shape disk target: various thicknesses

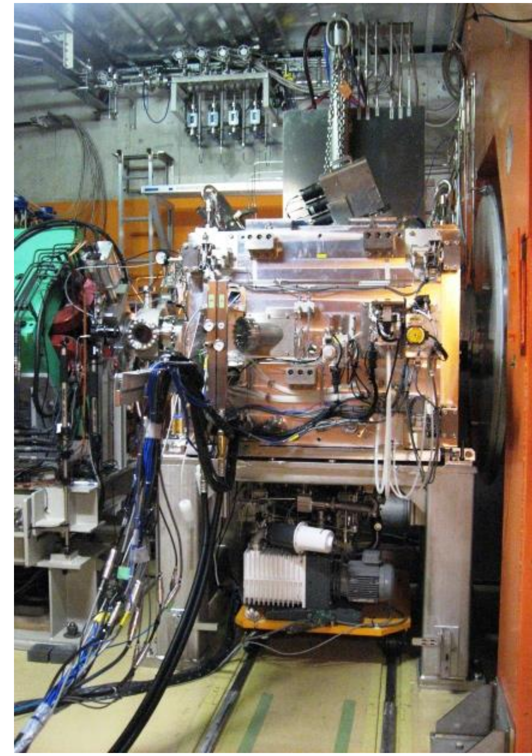


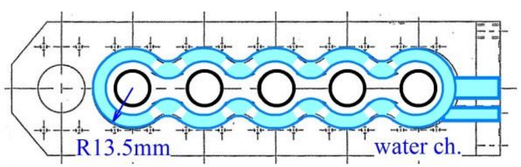



# BigRIPS Target System with maintenance cart



## Target ladder (fixed target)




The water way is cut in the ladder.

*Diameter : ~ 20 mm
*Thickness : 1 ~ 20, ~ 60 mm

Ladder target : for Low-power beam

## Rotating Target

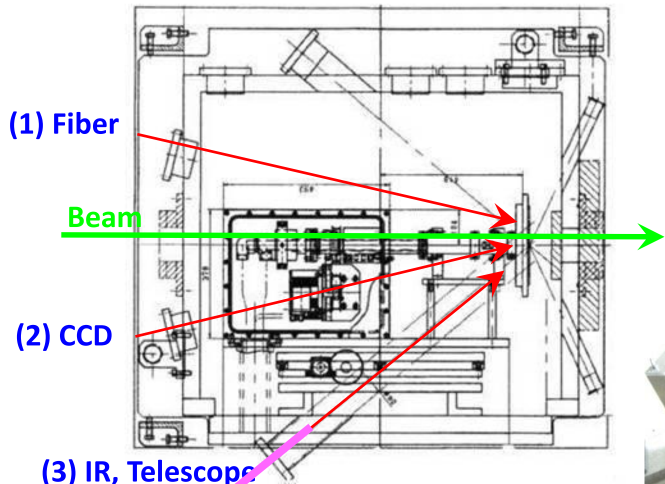
Disk target : for High-power beam


*Size : ϕ30cm
*Material : Be, W
*Step shaped edge
20,15,10 mm thick
for N, Ca, Ar beams
10, 7, 5 mm thick
for Kr, Xe, U beams
4, 3,, 2 mm thick
for U beam

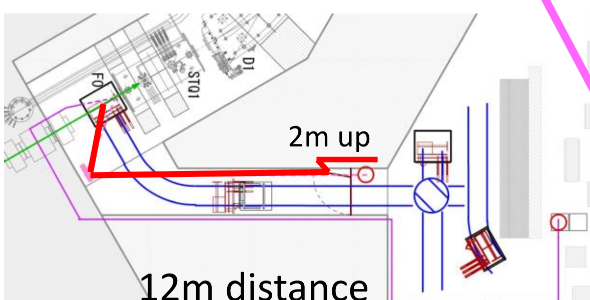
# Beam-spot temperature measurement

## 1) IR thermal image camera

Target chamber (upper view)




IR camera:
TVS-8500 AVIO (Japan)
Very weak for radiation
Can be used only for a short time.




## 2) Infrared Fiber Scope

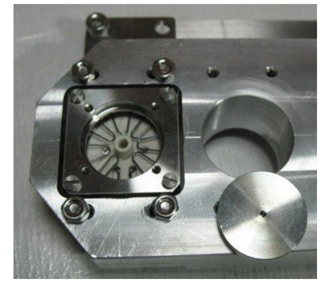
Continuous monitor

ϕ 5 mm

**Sapphire view port & Lenz unit mounted on the Target chamber**

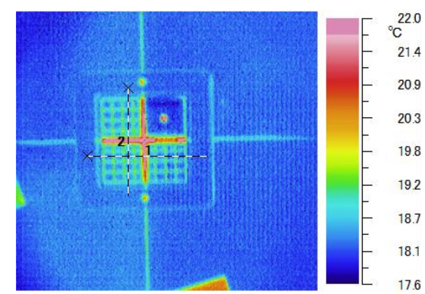
Calibration of Temperatures

- Emissivity
- attenuation in window mirrors, air



Heater + Be plate
+ Thermocouple

Spatial resolution check
long distance

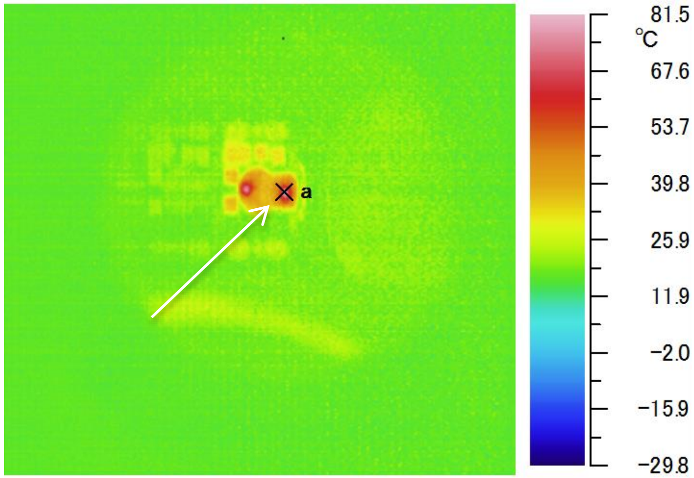



Spatial resolution (1px = 0.5mm)
0.5mm width slit
-> 2mm(H), 3mm(V)

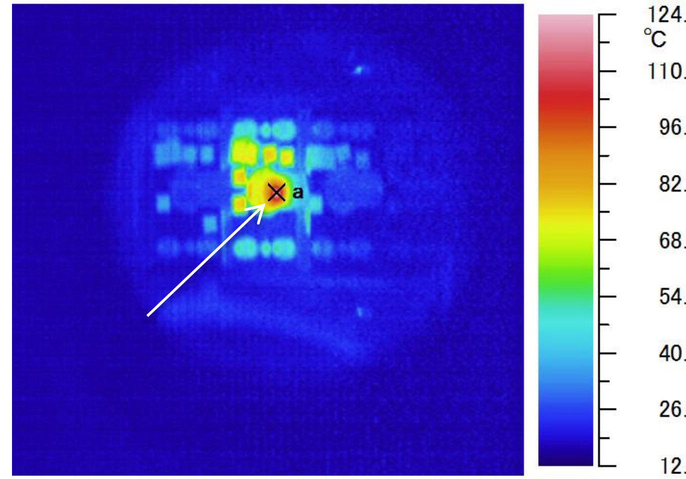
# Beam spot temperatures for $^{48}$Ca 345MeV/n Beam

## Ladder target (fixed target)

Be 15mm、280pnA、0.88kW 282℃



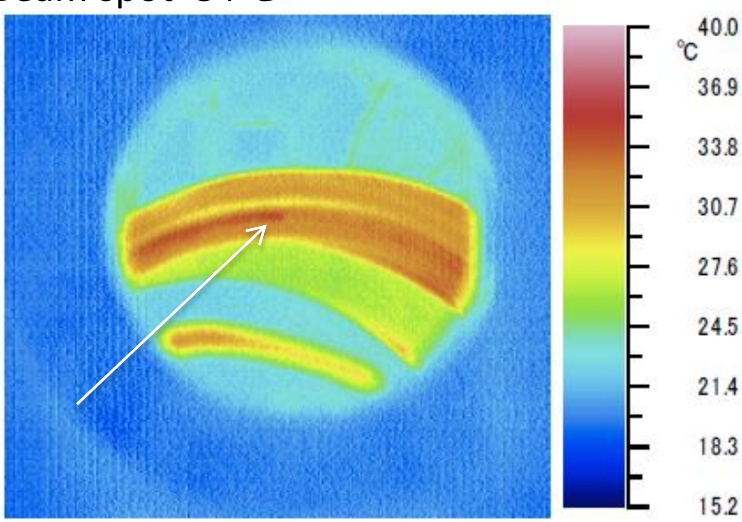

Be 30mm、283pnA、 1.9kW 234℃

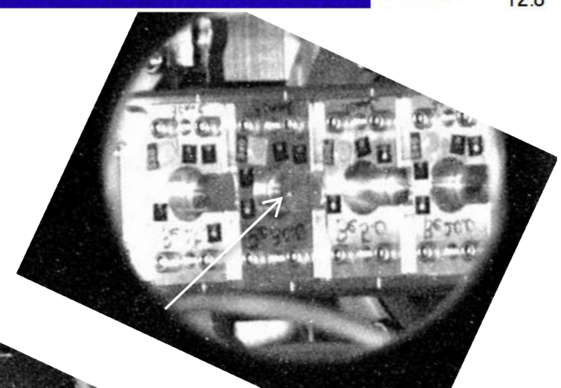


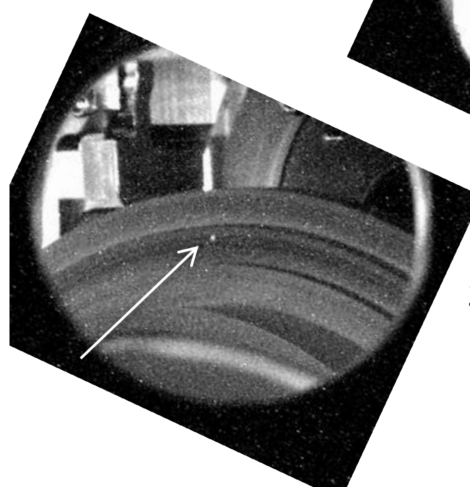

## Rotating target

Be 15mm, 420pnA, 100rpm 1.3kW

Beam spot 84℃





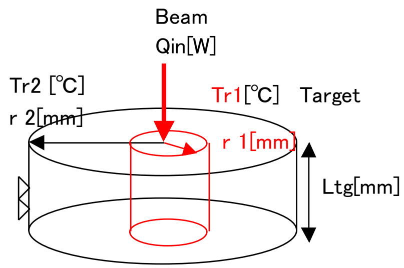
Normal Photo (visible light)

Scintillation of BeO is seen.
Useful for beam spot monitoring

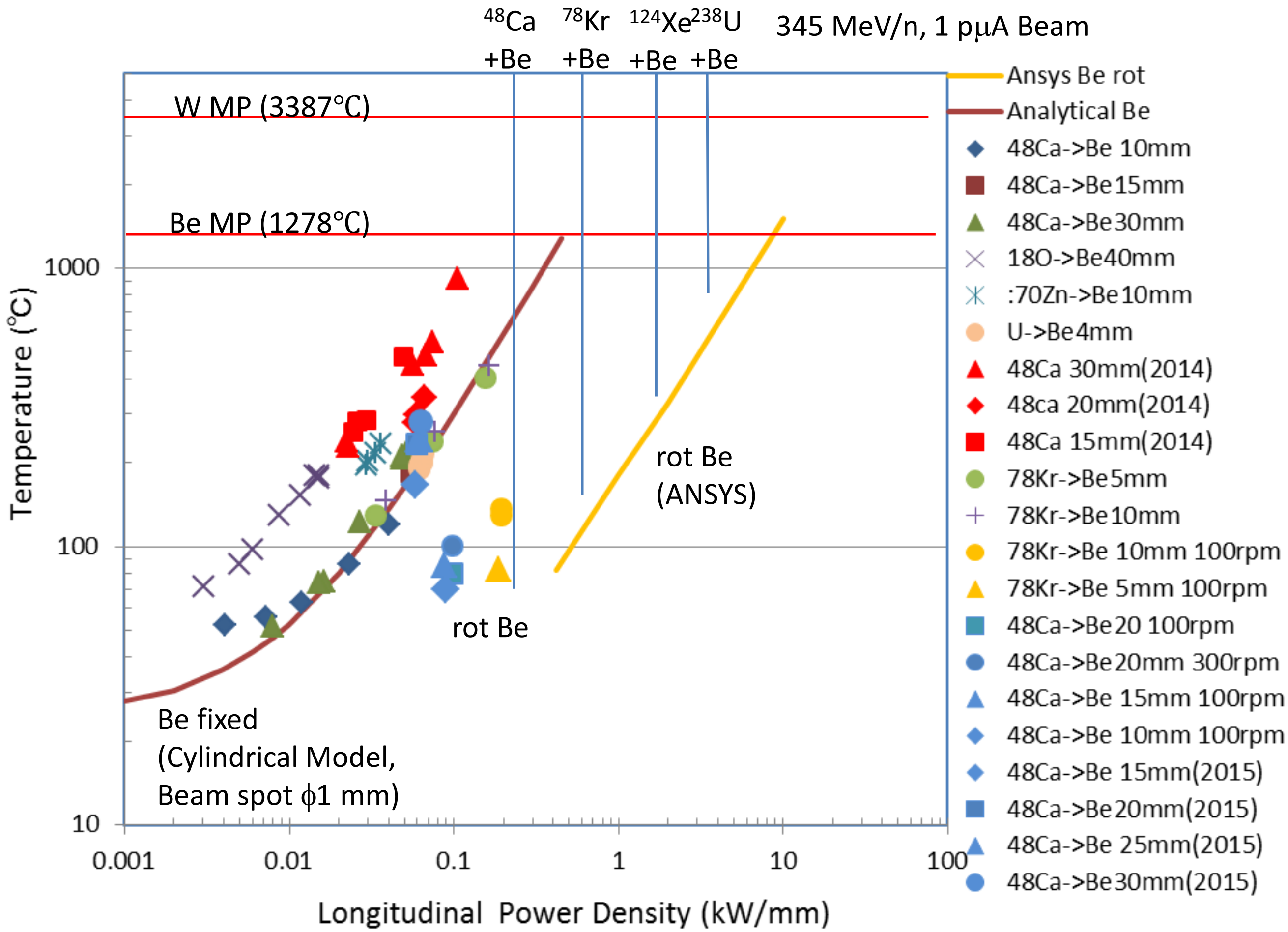
# Beam spot temperatures for various beam

Various combination of beams and target thicknesses →
Deposited Power/target thickness is relatively well measure.

**(( Cylindrical model ))**
**analytical model**




Tr1 : Beam Spot Temp.
= Tr2 + Qin*Ln(r2/r1) /(2πκLtg )
Qin = Ibeam * dE
∝ dE / Ltg

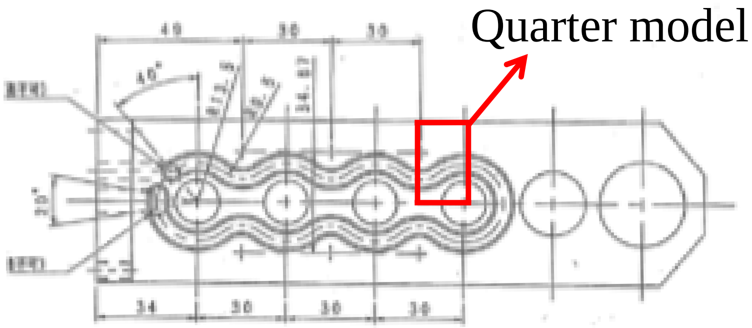


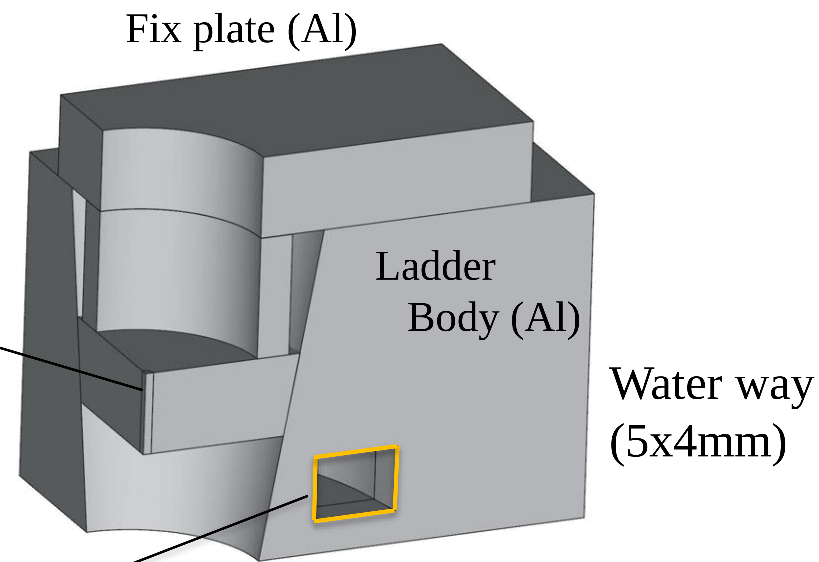

Fixed Target: agree with a simple cylindrical model
some data are higher -> thermal contact between target and ladder is bad?
ANSYS calculation was made by Zeren Korkulu (our new Pos. Doc.)
Rotating Target: higher temperature than the initial estimation -> need detailed simulations
Extensive simulations with ANSYS are now undergoing.

# ANSYS simulation of Fixed Target

By Zeren Korkulu

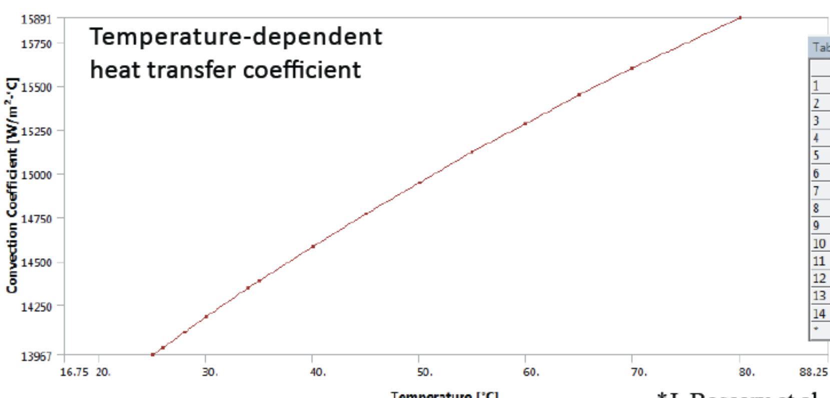
ANSYS simulations were performed for primary beams of **48Ca**, **78Kr** and **238U** and different thicknesses of Be target to evaluate the cooling capacity of the ladder target and beam power tolerance.



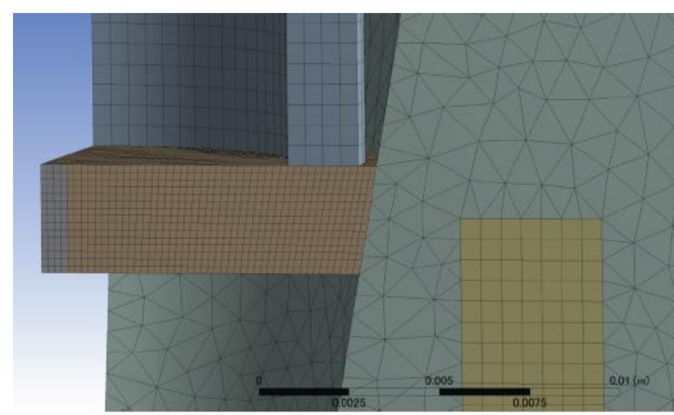

Temperature depending Thermal conductivity on Be
λ = 200 – 142 – 122 W/m K @ 27 – 200 – 400 °C
"Thermal and Structural Properties of Fusion related Materials"
http://www-ferp.ucsd.edu/LIB/PROPS/PANOS/matintro.html

Cooling Water : V= 3.5 m/s P= 0.4MPa, T=25°C




Tabular Data

| | Temperature [°C] | Convection Coefficient [W/m²·°C] |
|---|---|---|
| 1 | 25. | 13967 |
| 2 | 26. | 14011 |
| 3 | 28. | 14098 |
| 4 | 30. | 14182 |
| 5 | 34. | 14350 |
| 6 | 35. | 14390 |
| 7 | 40. | 14586 |
| 8 | 45. | 14773 |
| 9 | 50. | 14952 |
| 10 | 55. | 15126 |
| 11 | 60. | 15286 |
| 12 | 65. | 15450 |
| 13 | 70. | 15602 |
| 14 | 80. | 15891 |
| * | | |

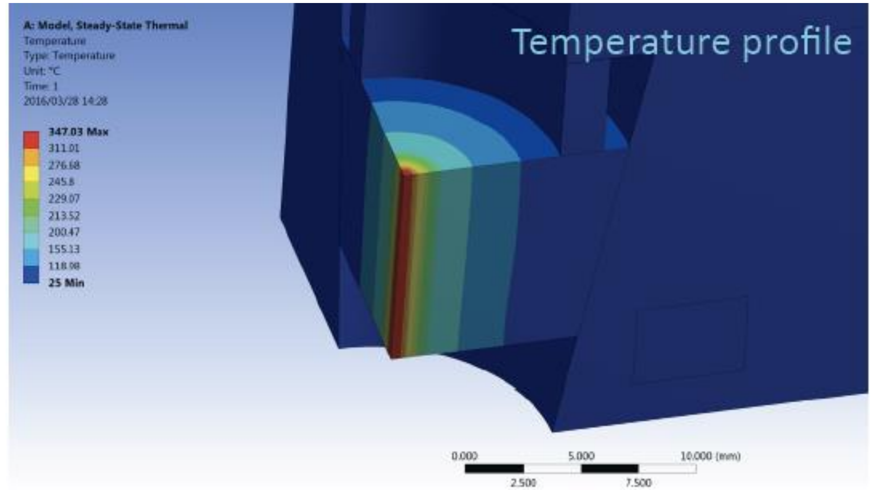


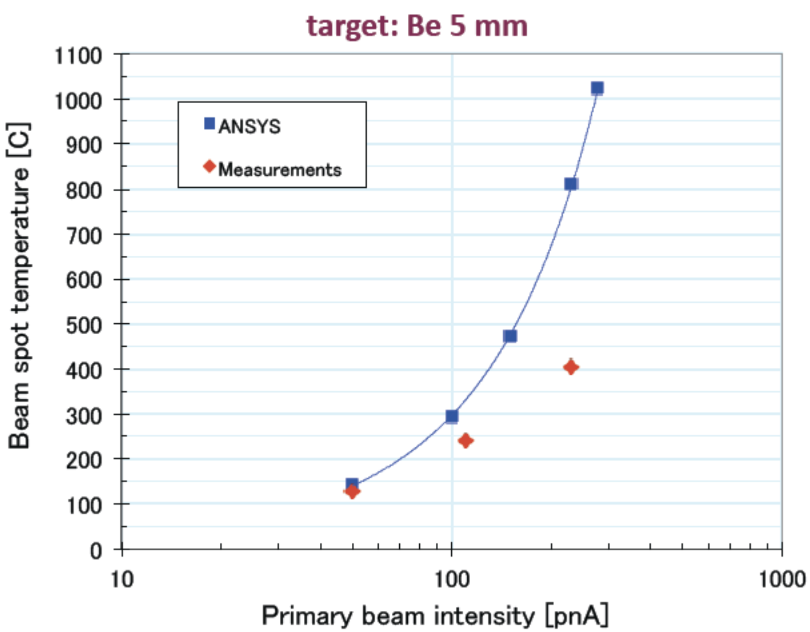

*J. Boscary et al., Fusion Eng. Des. 43, (1998), 147.

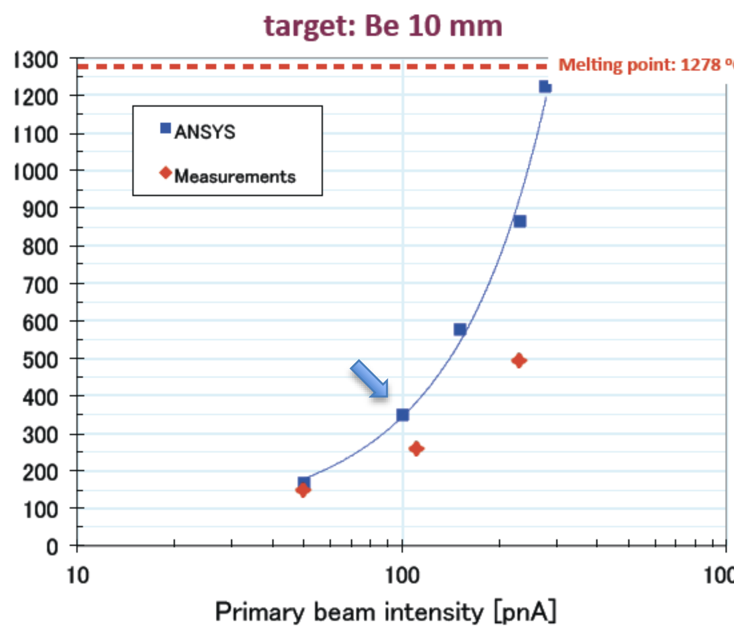
# Results of ANSYS calculations

$^{78}$Kr Beam: 345 MeV/n 100 pnA
spot size 1.0 mm
target 10 mm Be
deposit power 1.6 kW

Beam spot temperature is around 347°C



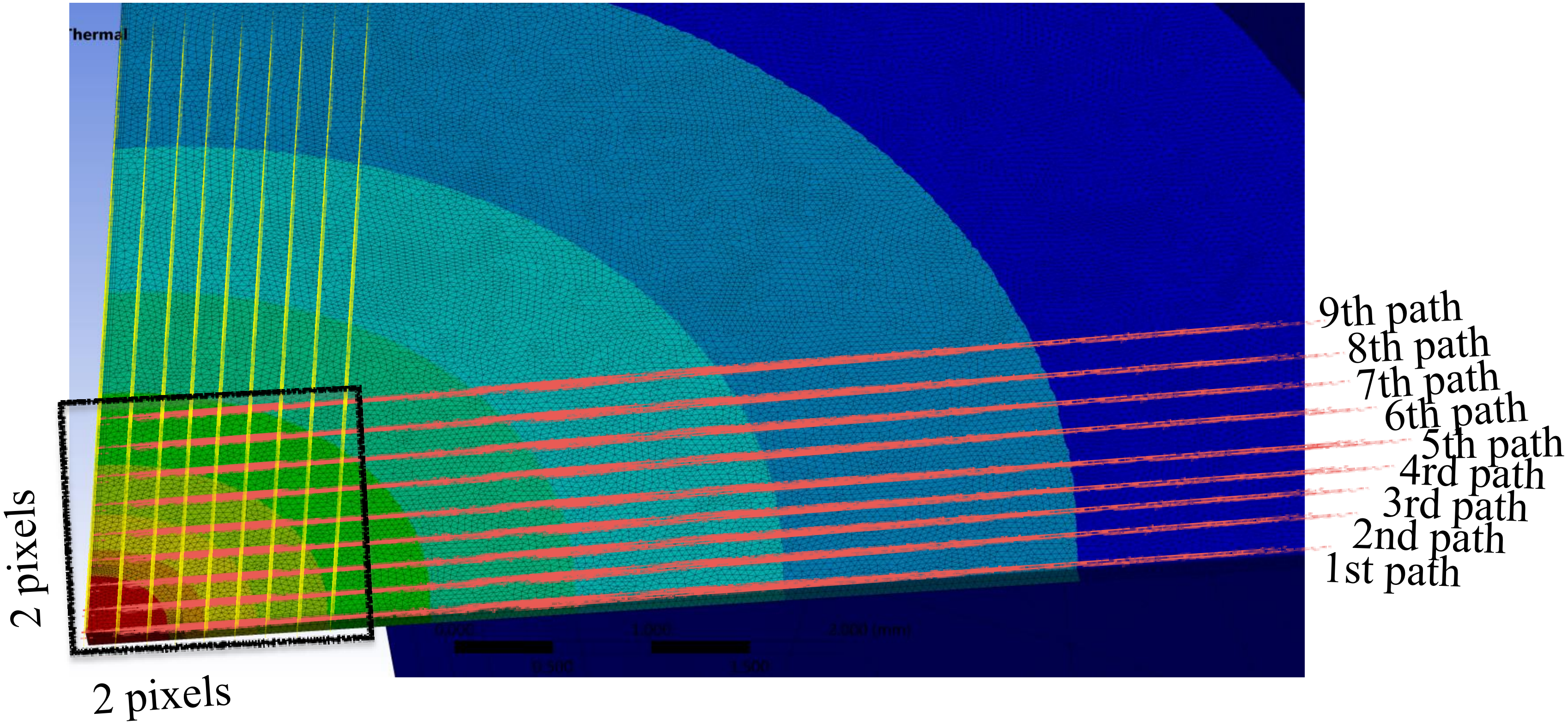




***Beam intensities: 50, 110 and 230 pnA***

# Beam spot temperatures

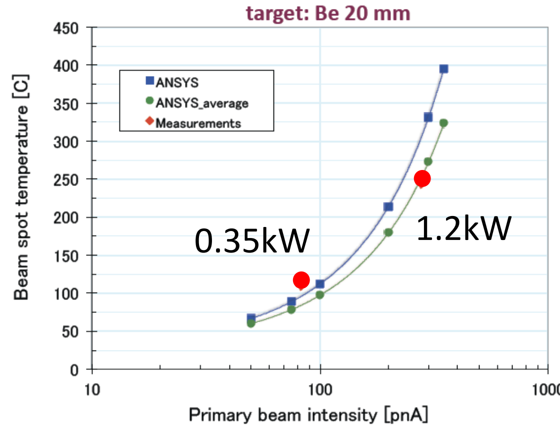
Simulations are over estimated the beam spot temperature.
Beam spot size of 1mm is smaller than the spatial resolution of thermal camera (2 mm)
ANSYS mesh size is even smaller. (around 0.3mm)
To compare with measured temperatures, calculation results need to be averaged.

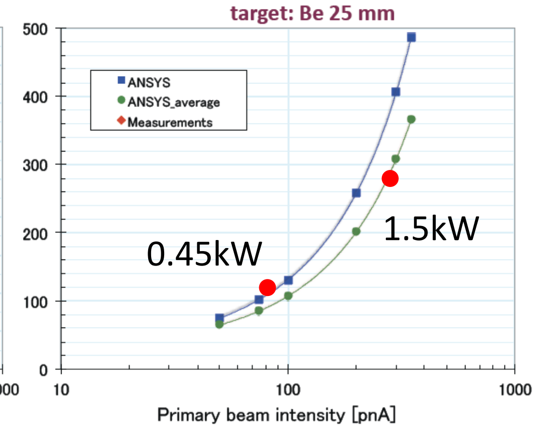



**The resolution of thermal camera is around 2 mm and it is around 4 pixels on the beam spot area (1 pixel = 0.65 mm).**

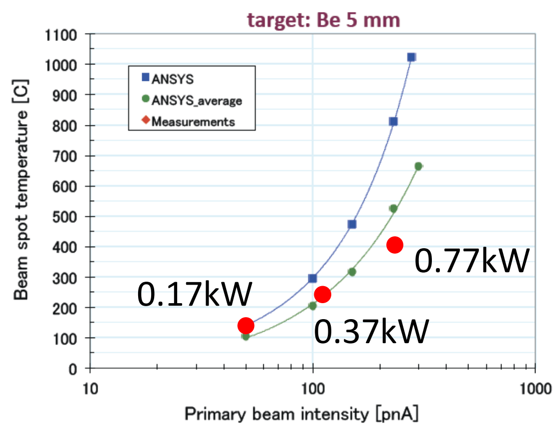
# Results of beam spot temperature

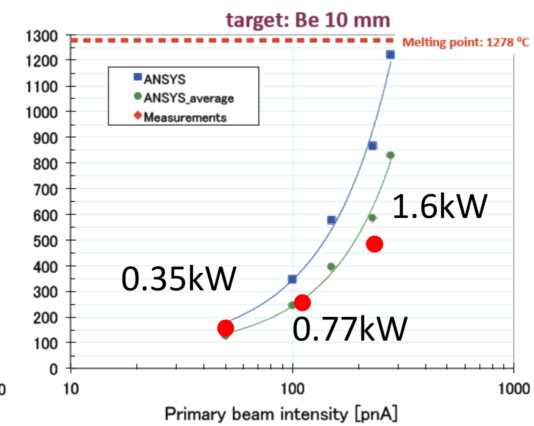
$^{48}$Ca Beam 345 MeV/n
spot size: 1.0 mm
Beam Intensity: 83 pnA, 280 pnA



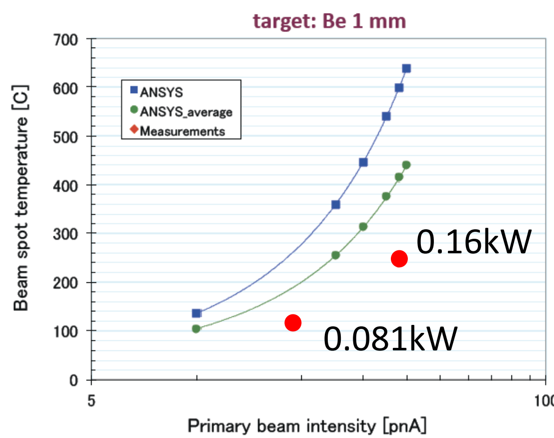



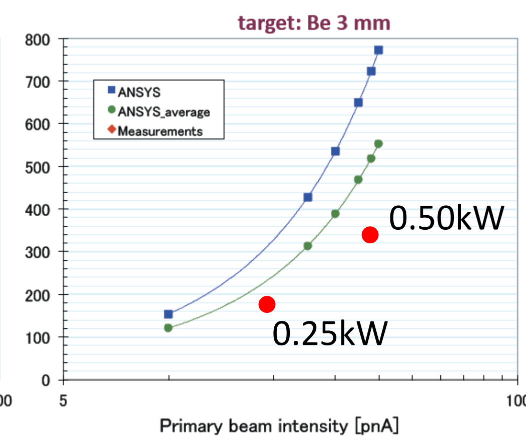

$^{78}$Kr Beam 345 MeV/n
spot size: 1.0 mm
Beam Intensity: 50, 110, 230 pnA



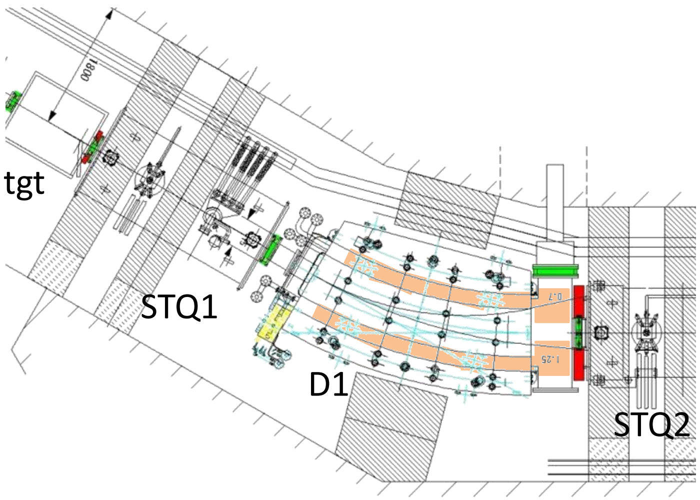

$^{238}$U Beam: 345 MeV/n 20pnA
spot size: 1.5 mm
Beam Intensity: 19 pnA, 38 pnA

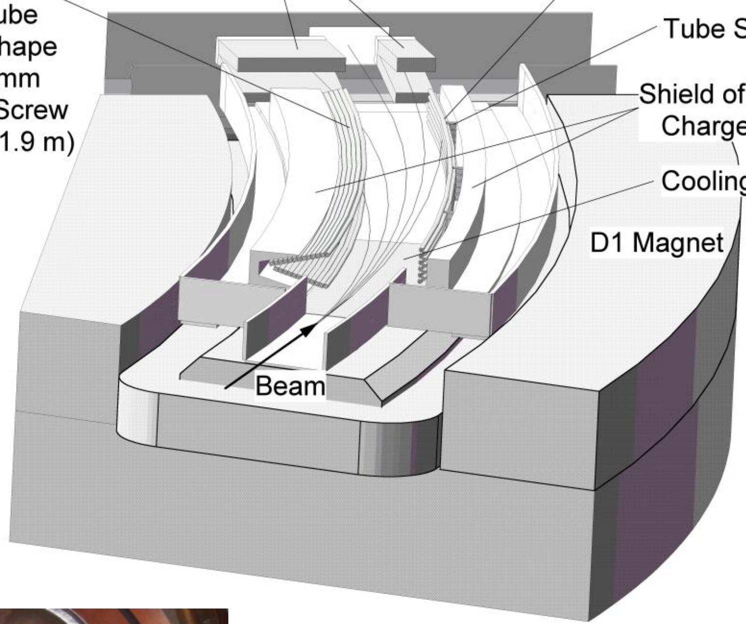


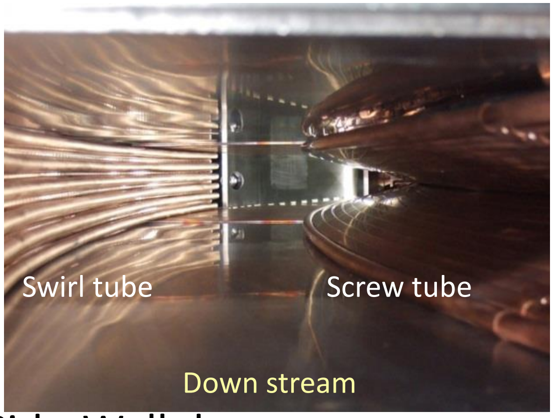



# BigRIPS Beam Dump

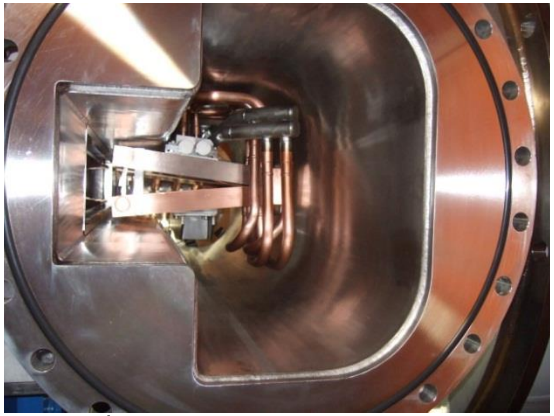
Water-cooled stationary dumps are placed inside of D1 magnet gap and just after the D1 magnet




Side-Wall dump

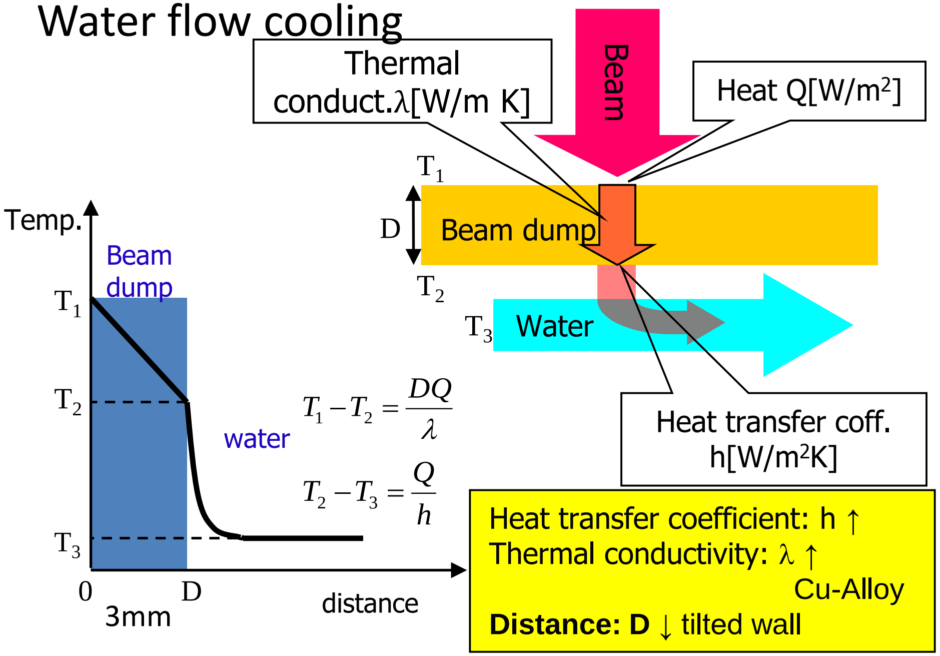


Exit dump

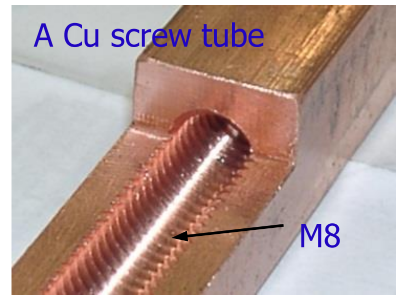
Exit dump at maintenance position

# Efficient cooling channel

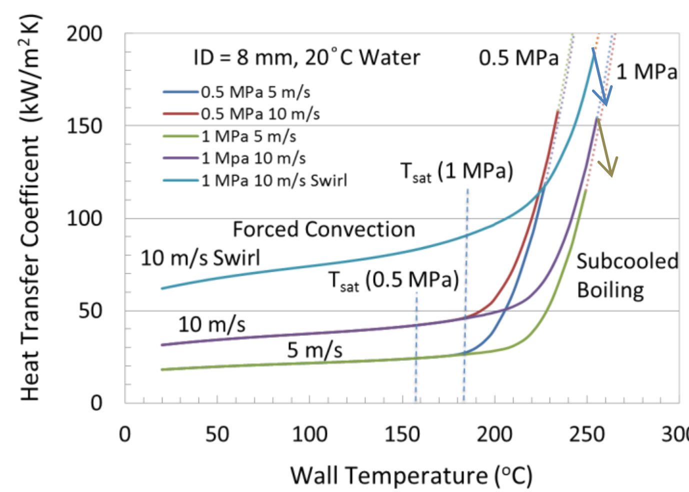
## Water flow cooling




- Cooling tubes with high heat transfer coefficient





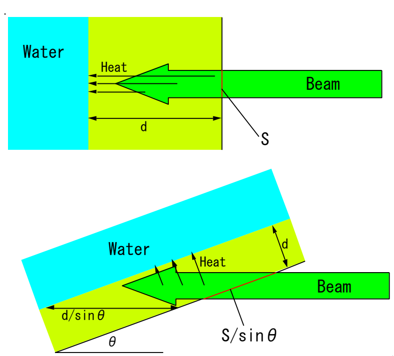



J. Boscary et al., Fusion Eng. Des. 43 (1998) 147

High pressure 1 MPa
High Velocity 10 m/s
→ High heat transfer coefficient
Critical Heat Flux. of swirl tube
~55 MW/m²

J. Boscary et al., Fusion Eng. Des. 43 (1998) 147

- Tilted Wall



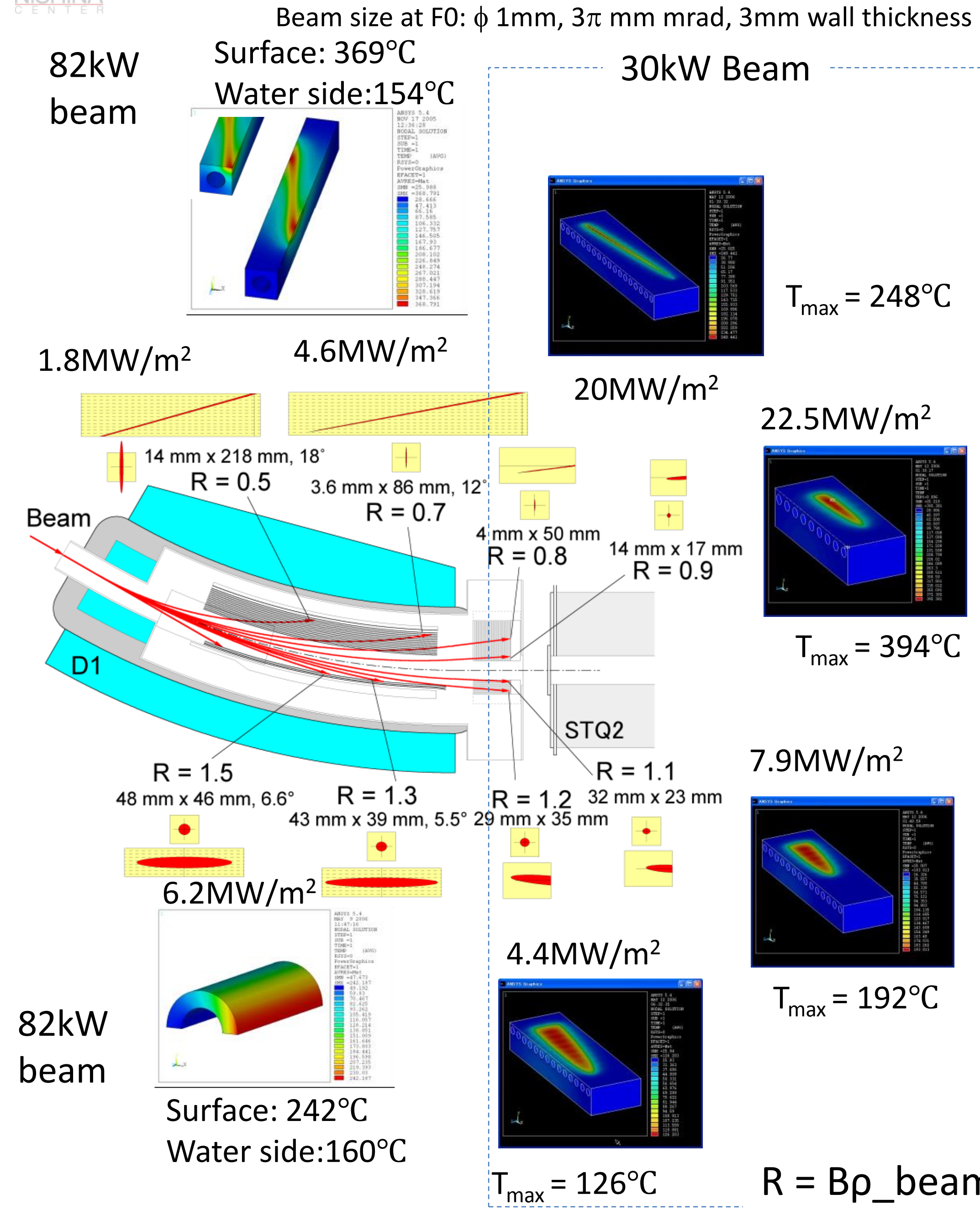

Reduces Power density
Prolongs effective length
by 1/sinθ

sin 20° = 0.34
sin 6° = 0.1

stop beams from $^{12}C$ to $^{238}U$.

# Design of Beam Dump

By N. Fukuda, H. Mizoi, K. Yoshida , and T. Kubo
NIM B317(2013)373

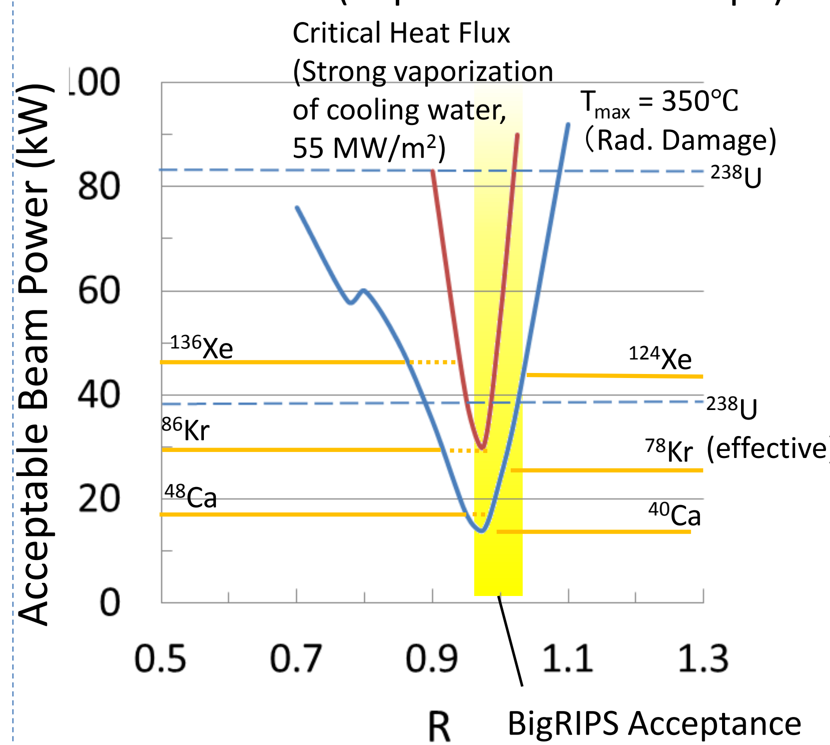



Operation Limit:

a) Critical Heat Flux at cooling channel
   Heat flux at water channel < 55 MW/m²

b) Radiation Damage :
   T > 350 deg. effect is large.
   Dump (surface) temperature < 350 deg.

→ Acceptable power density
   a) ~ 45 MW/m²  b) ~20 MW/m²
   (depends on beam shape)



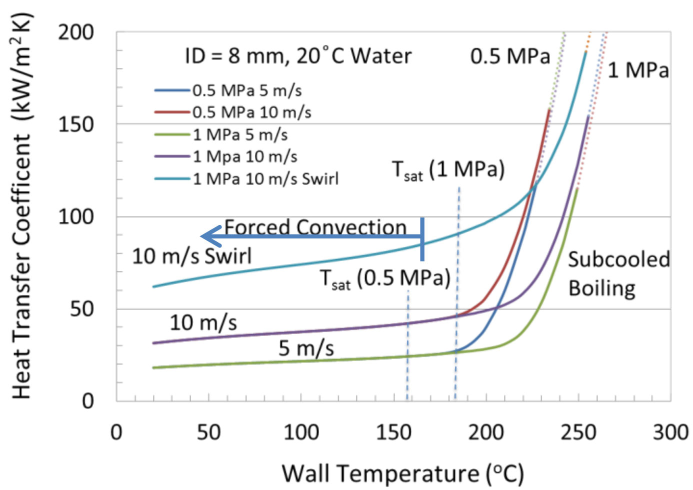

R = Bρ_beam / Bρ_RI beam

# BigRIPS Beam Dump

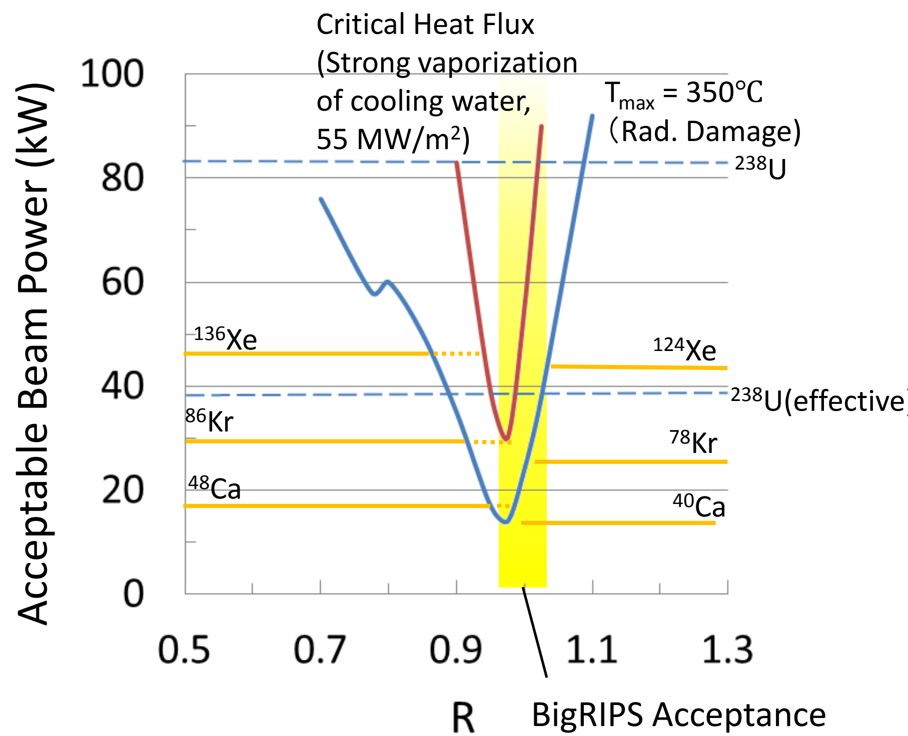
- Beam dump accept most of beams of 1pμA except for $^{238}U$.
  charge state distribution of $^{238}U^{89,90,91+}$ after the production target helps to reduce the heat density.

- A special exit beam dump for an intense $^{238}U$ beam
  1 mm Wall thickness to improve the cooling power (design only)

- When Tmax=350°C, the wall temperature is about 170 °C. Cooling is made by forced convection.



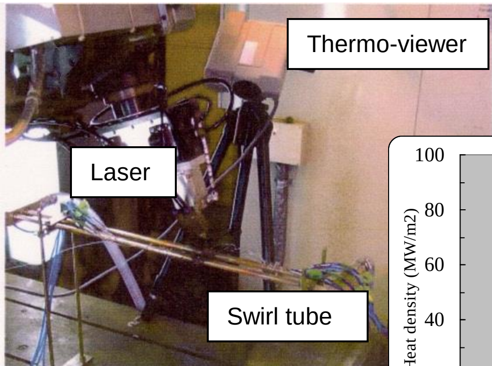

Results of simulation greatly depend on the ambiguity of heat transfer coefficient.
Need to be verified.

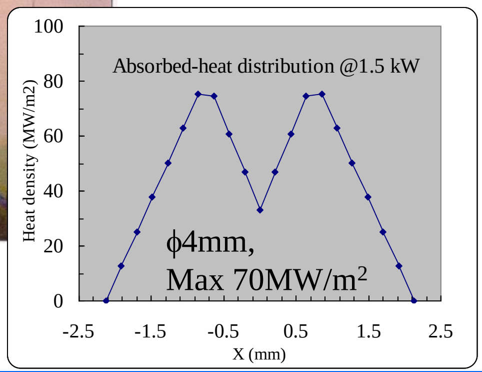


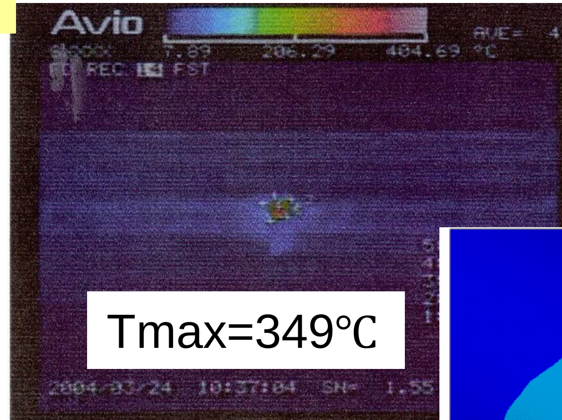

R = Bρ_beam / Bρ_RI beam

# Evaluation of the cooling capacity: off line test of the test pieces

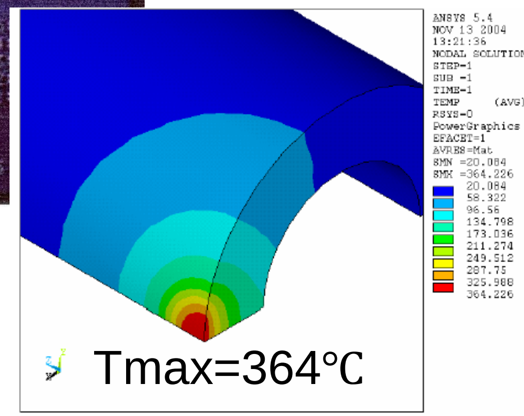
## Irradiation of a 1.5 kW $CO_2$-leaser beam



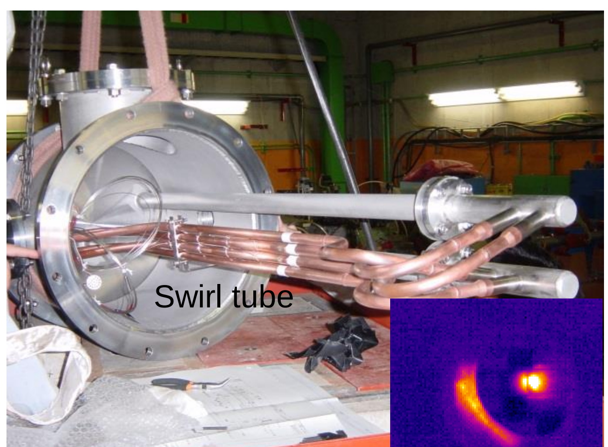




ANSYS calculation reproduces the temperature distribution well.

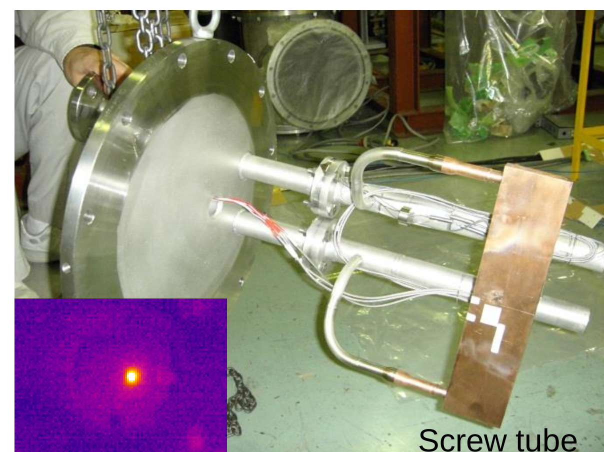



## Irradiation of $^{40}$Ar beam with 64MeV/n, 0.5-1pμA from RRC

Dumps stand these heat load.
Max. temperatures observed are 110-200℃.
Preliminary ANSYS calculation gives
factor 4-6 higher temperature.




Φ2mm,1kW,325MW/m²,T=200℃

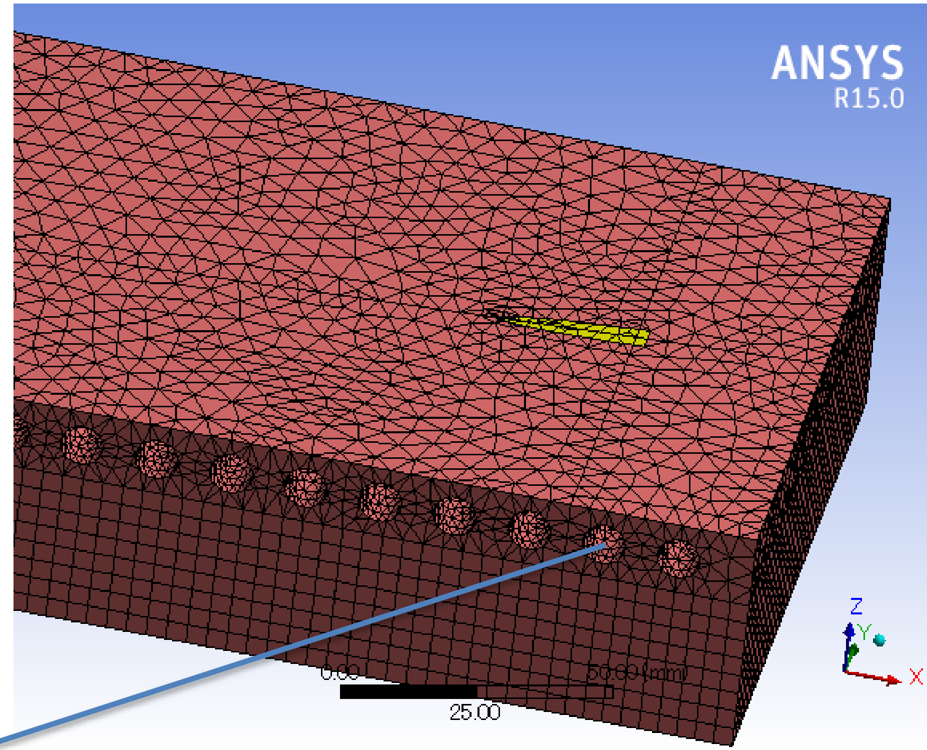



Φ5mm,2120kW,108MW/m²,T=116℃

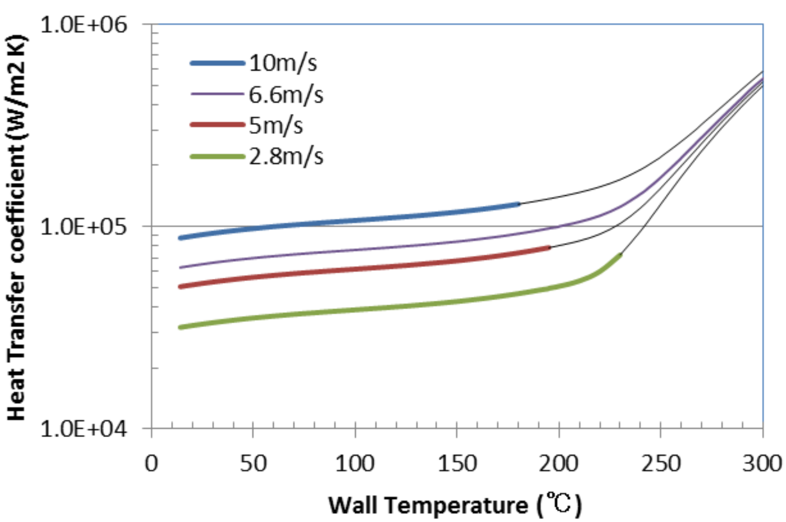
# $^{48}$Ca 345MeV 500pnA (8.3kW) Beam Test

Beam was stopped near the thermocopule
mounted on exit beam dump.
(Beam Brho / D1 Brho =0.845)
Beam Spot: estimated from the beam emittance
measured at F2
F0 in $\sigma$ x: 0.74mm, 3.3 $\pi$ mm mrad
y: 0.45mm, 1.9 $\pi$ mm mrad
Tuning STQ1 Field: three different spot sizes
x x y : 4.5 x 141, 8.8 x 28.1, 1.9 x 23.6

Thermal Conductivity: Cu-Cr-Zr 320 W/m K
http://conductivity-app.org/




Heat Transfer Coefficients



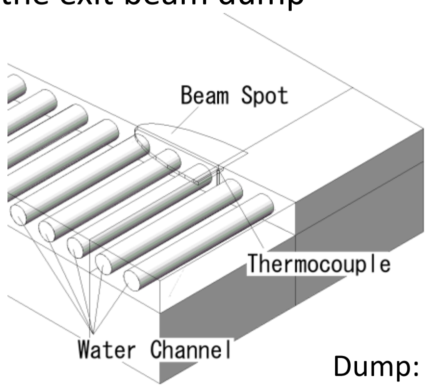

Cooling Water speeds: 3 points.
10, 5, 2.8 m/s
Temperature 14°C
Pressure 1MPa

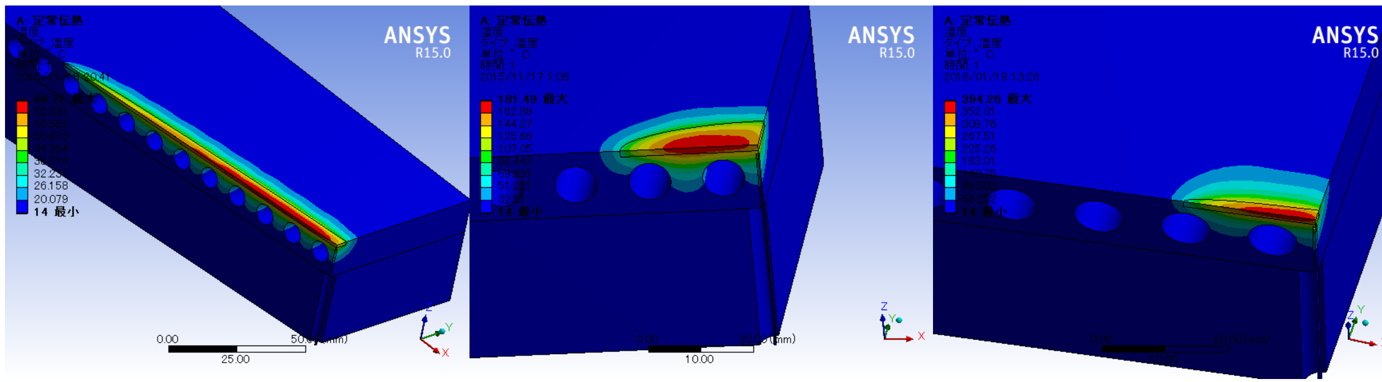
Heat transfer coefficients are calculated by using empirical formula.
J. Boscary et al., Fusion Eng. Des. 43 (1998) 147
K. Masaki et al., Fusion Eng. Des. 61-62 (2002) 171

# Temperature measurement with $^{48}Ca$ 345MeV/n 500pnA (8.3kW)

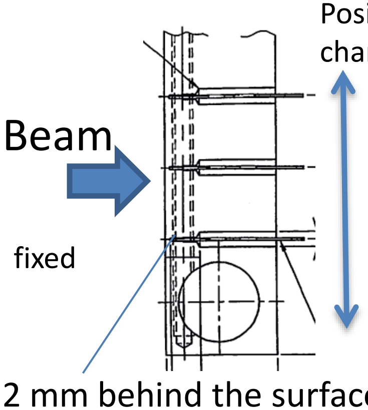
| Beam spot size | 4.5x141 | 8.8x28.1 | 1.9x23.6 |
|---|---|---|---|
| Heat density ($MW/m^2$) | 3.88 | 10.1 | 53.5 |
| Cooling water speed (m/s) | 10 | 10 | 10 |
| Max. Temp (°C) : | 68.7 | 182 | 394 |
| Max. Temp at cooling channel(°C) : | 44.2 | 129 | 179 |
| Thermocouple Temp.(°C) : | 37.43 | 96 | 168 |
| Max heat flux at cooling channel($MW/m^2$): | 2.99 | 9.32 | 23.2 |

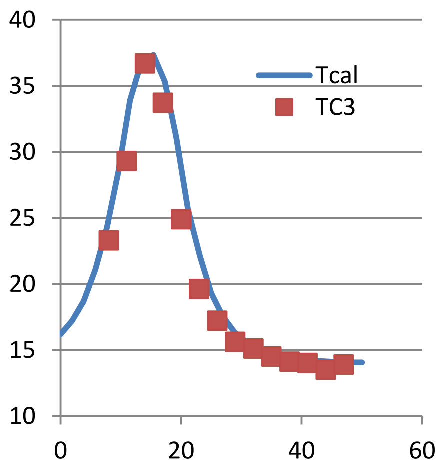
Thermo-couples mounted on the exit beam dump

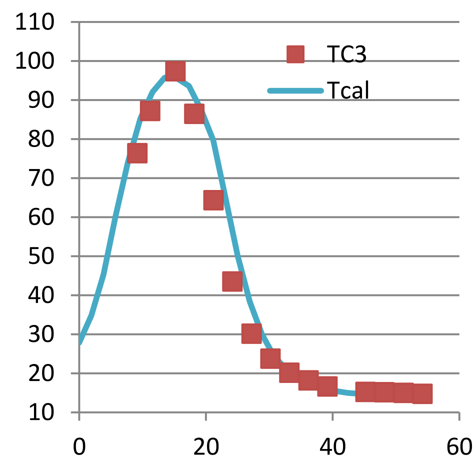


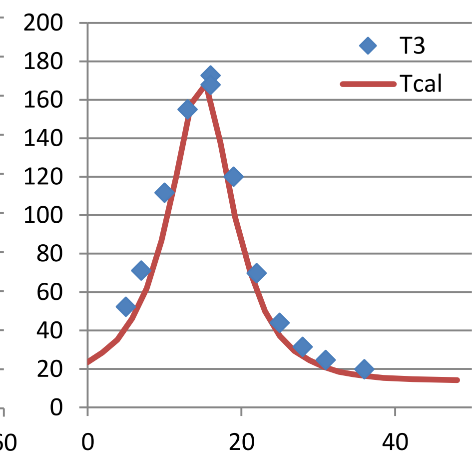




Dump: Position change



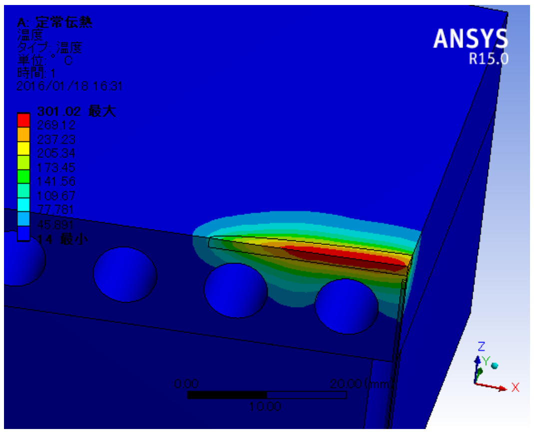



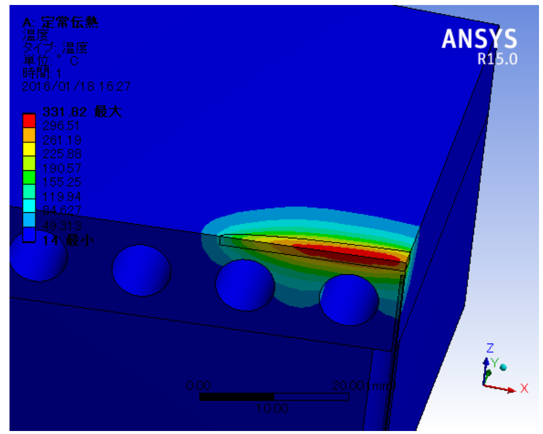



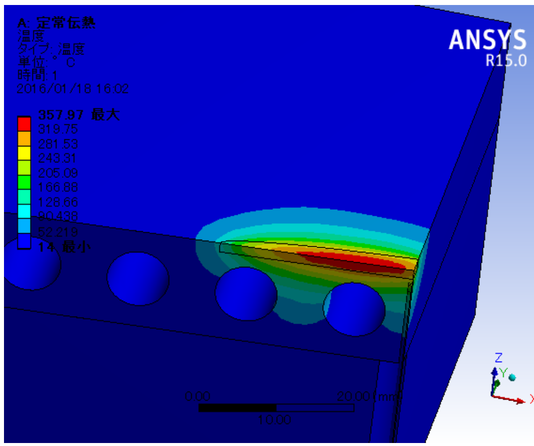

Change the beam optics -> various beam spots, Heat densities : good agreements

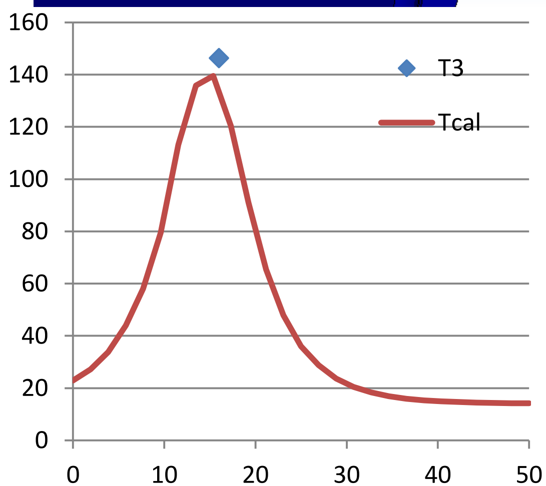
# Water velocity dependence 3-10 m/s

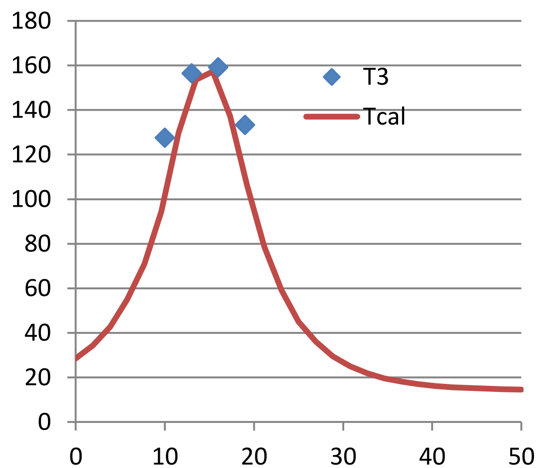
| | | | |
|---|---|---|---|
| Beam Spot size | 3.0x 27.2 | 3.0 x 27.2 | 3.0x27.2 |
| Heat Density(MW/m2) | 29.9 | 29.9 | 29.9 |
| Cooling water speed(m/s) | 10 | 5 | 2.8 |
| Max temp.(°C) : | 301 | 332 | 358 |
| Max temp. at cooling channel(°C) : | 154 | 195 | 224 |
| Thermocouple Temp.(°C) : | 140 | 157 | 175 |
| Max. Heat flow at cooling cha.(MW/m2): | 17.1 | 14.7 | 14.4 |

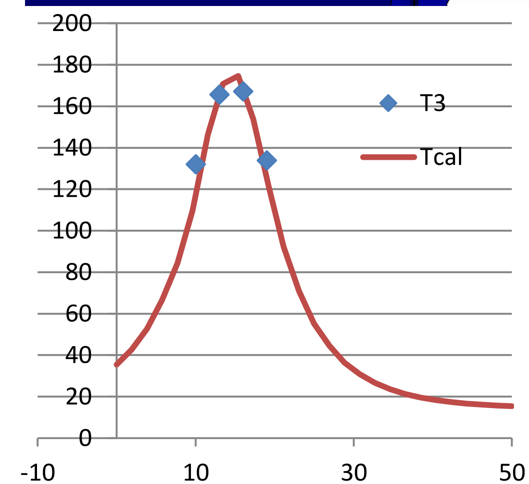


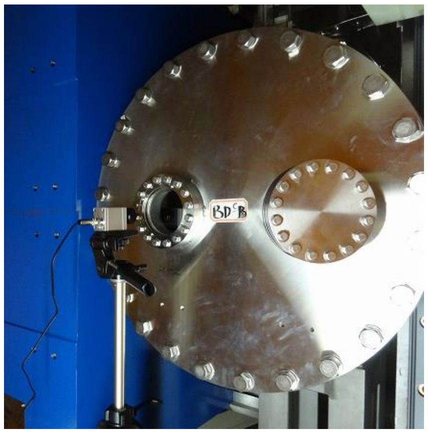



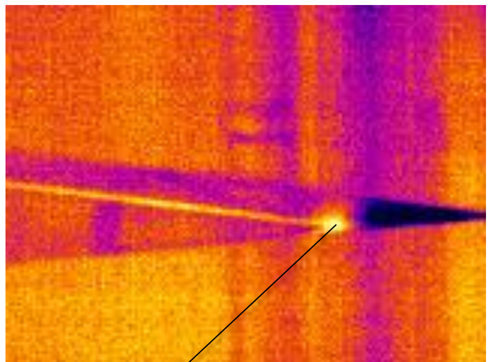

Good agreements -> estimation of heat transfer coefficients is appropriate.

# $^{238}$U 345MeV/n 33pnA 2.7kW Test

Temperatures of outside exit dump was measured by thermal camera and thermocouples.
(Body temperature + surface temperature )

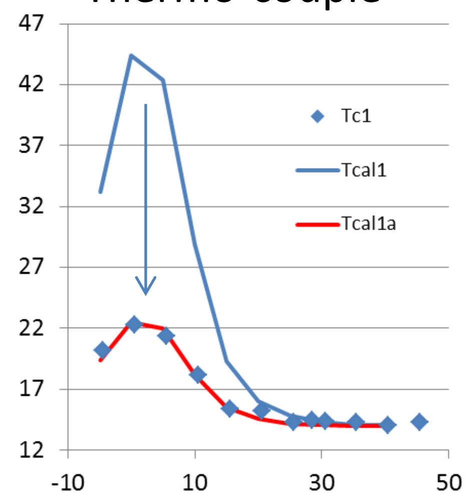


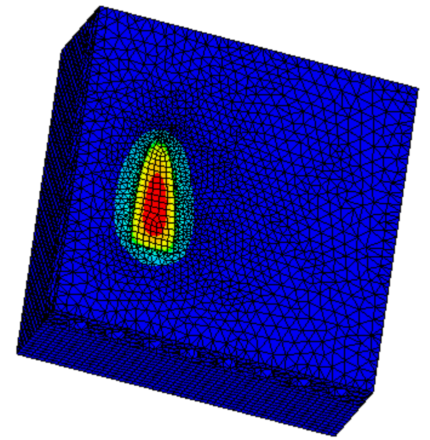
Thermal Camera

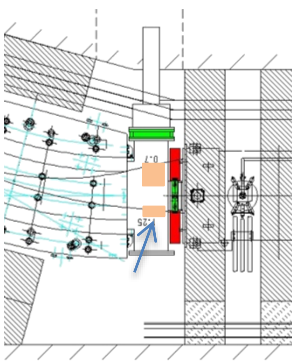


28°C

Thermo-couple





Optris PI160
Infrared camera

| | | | |
|---|---|---|---|
| Beam Power (kW) | 2.7 | → | ( 0.75 ) |
| Beam Spot size | 8.0 x 43 | | |
| Heat Density(MW/m2) | 2.5 | → | ( 0.69 ) |
| Cooling water speed(m/s) | 6.6 | | 6.6 |
| Max temp.(°C) : | 66 | | 29 |
| Max temp. at cooling channel(°C) : | 41 | | 22 |
| Thermocouple Temp.(°C) : | 44 | | 23 |
| Max. Heat flow at cooling cha.(MW/m2): | 1.9 | | 0.53 |

## Very Preliminary

# Summary

- Production Target
  - Beam spot temperatures were measured and compared with thermal model calculations.
  - Fixed target
    - ANSYS simulation reproduces the observed temperature if the spatial resolution of thermo-camera is taking into account.
    - However, for 238U beam, simulations overestimate the observed temperatures
  - Rotating target
    - Detailed simulation
- Beam Dump
  - Beam spot temperature was measured.
  - Measured temperatures were well reproduced by thermal model calculation for $^{48}Ca$ beam case (8.3kW). It suggests that our estimation of the heat transfer coefficient is appropriate.
  - For $^{238}U$ beam (2.7kW), a preliminary result of simulation fails to reproduce the observed temperature.