

# Fundamentals of Cryomodule

KEK, High Energy Accelerator  
Research Organization

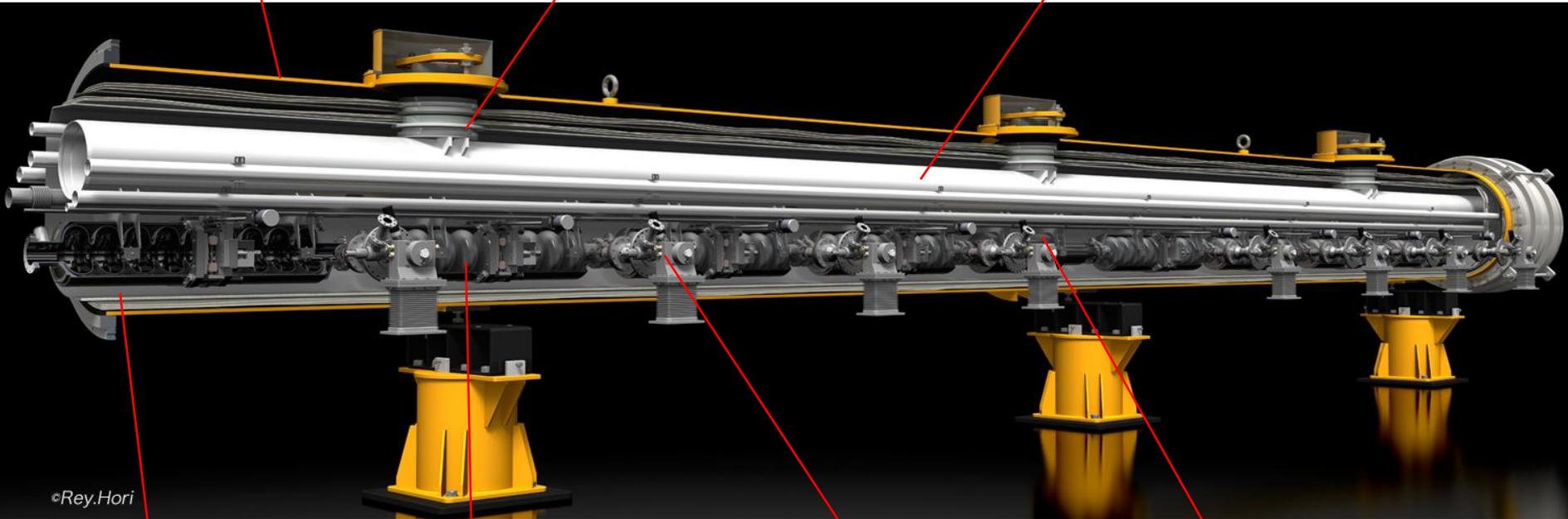
Norihito Ohuchi

# Basic Function of Cryomodule

1. The minimum unit in the accelerator components which has an interface with the room temperature.
2. Making the work space where the superconducting cavities operate at 2K:
  - Hold the superconducting cavities in the vacuum and thermal insulated environment.
  - Keep the cavities in a good alignment with respect to the design beam line.
  - Have an interface for supplying RF power to cavities between cold and warm components.

# ILC cryomodule overview

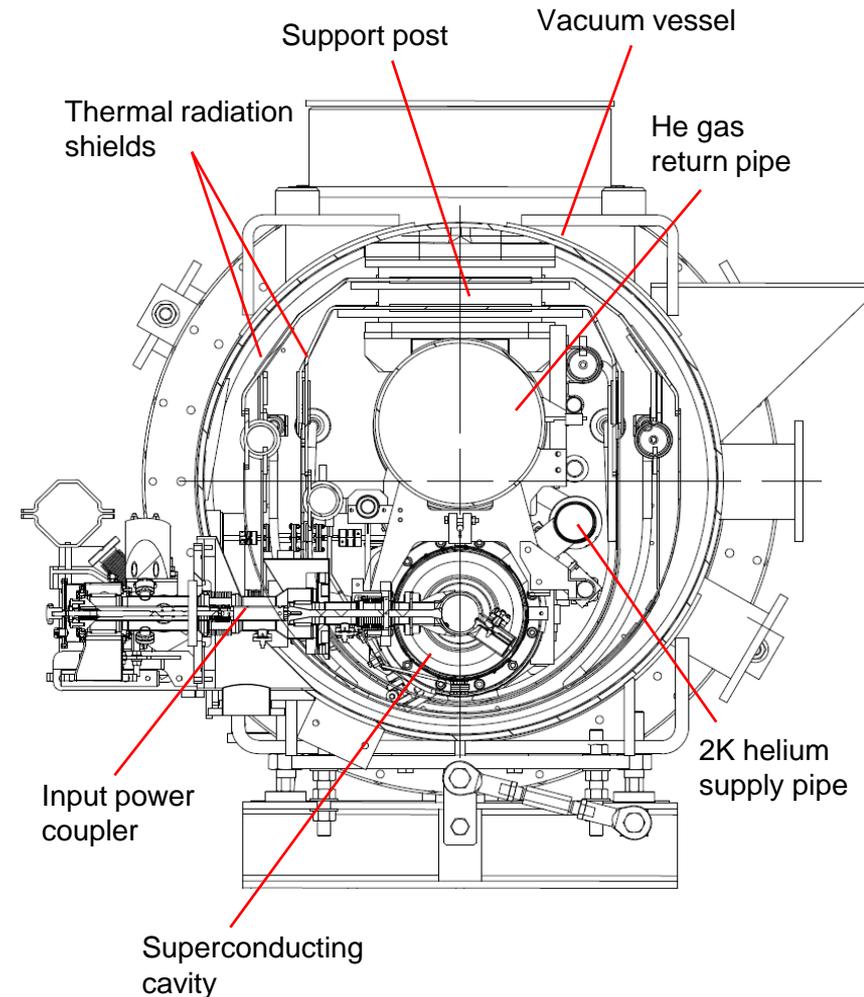
Vacuum vessel      Support post      Helium gas return pipe (GRP)



Thermal radiation shields      Superconducting cavity      Input power coupler Wave guide      Superconducting quadrupole

# Cryomodule components

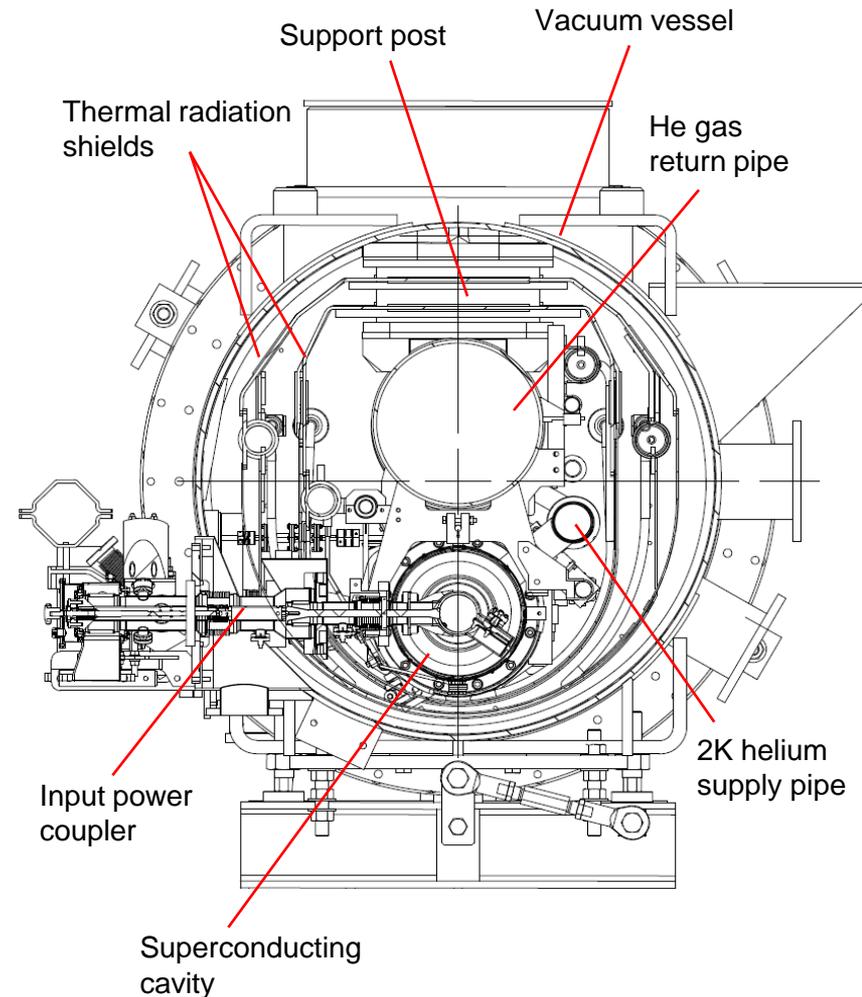
- **Vacuum vessel (Iron pipe)**
  - Outer diameter = 965.2mm, Length=11.8m
  - Connection between cryomodules
    - Vacuum bellow
  - Total length=12.7m
  - Magnetic shielding
- **Support post**
  - Supporting the all cold mass in the vacuum vessel
  - Material: FRP(G-10)
- **Thermal radiation shield**
  - Aluminum plate + Multi-layer insulation of aluminum-evaporated film (Super Insulation)
  - 40K-80K, 4K-5K helium gas cooling



DESY-TESLA-TYPE-III  
Cryomodule Cross Section

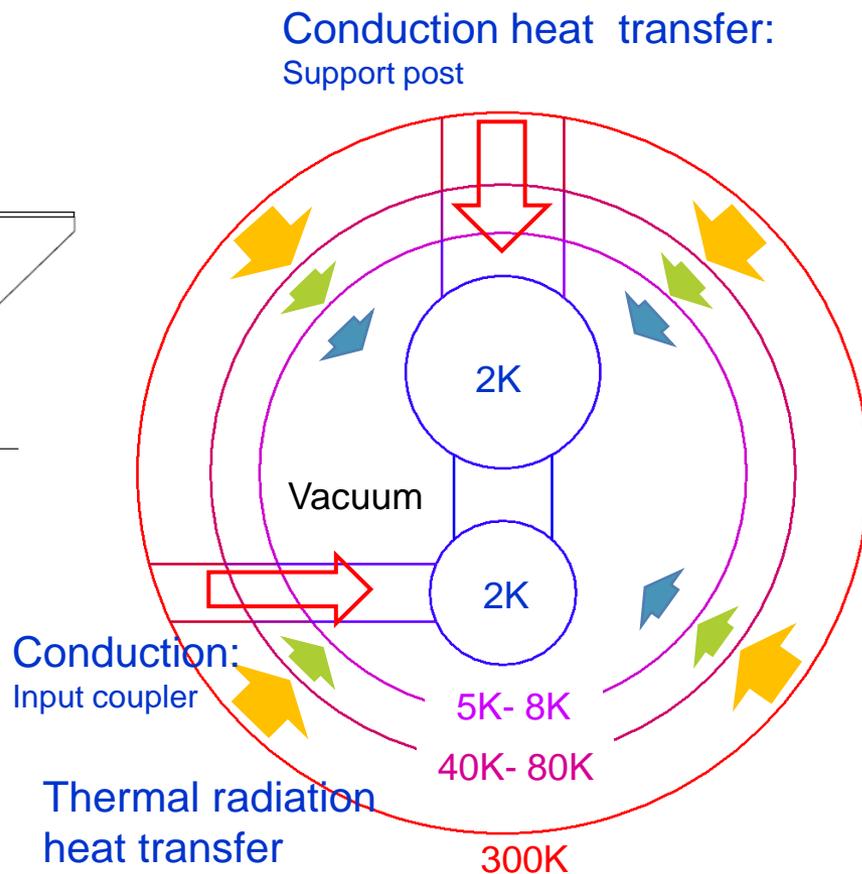
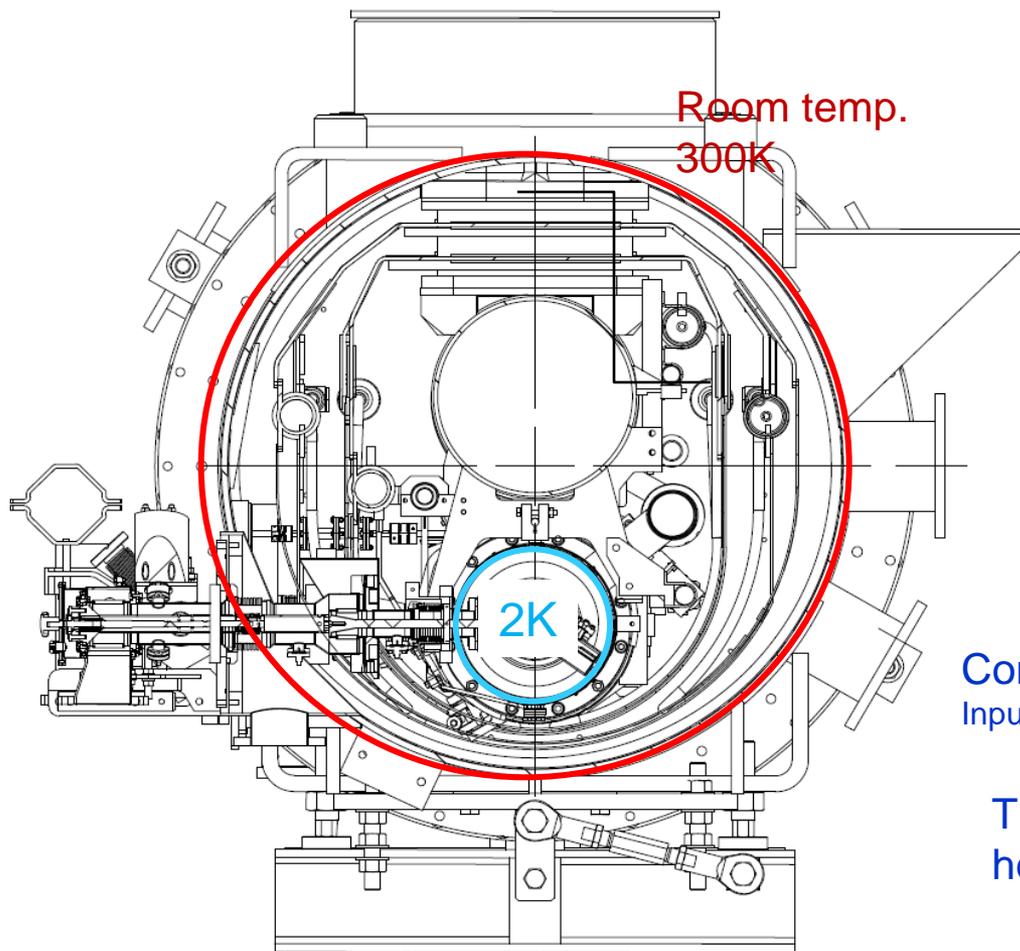
# Cryomodule components

- **2K helium gas return pipe (GRP)**
  - Gas channel for evaporated helium gas
  - Inner diameter=300mm
  - Material: Stainless steel
  - Supporting the cavities and quadrupole
- **Superconducting cavity package (8 or 9 for one cryomodule)**
  - Liquid helium container, input power coupler, HOM coupler, frequency tuner
- **Another cooling pipes**
  - 2K 2-phase helium supply
  - 2.2K supply
  - 5K forward and 8K return for 5K shield
  - 40K forward and 80K return for 80K shield
  - Cool down and warm up
- **Superconducting quadrupole and beam position monitor**
  - Current lead, corrector coils



DESY-TESLA-TYPE-III  
Cryomodule Cross Section

# Making thermal insulated environment for superconducting cavity



# Conduction heat transfer

$T=2\sim 300\text{K}$

Cu  $K= 4 \times 10^2 \sim 1.4 \times 10^3 \text{ W}/(\text{m}\cdot\text{K})$

Al  $K= 2.4 \times 10^2 \sim 4 \times 10^3 \text{ W}/(\text{m}\cdot\text{K})$

SUS  $K= 0.2\sim 1.5 \times 10 \text{ W}/(\text{m}\cdot\text{K})$

$$q = -KA(\partial T/\partial x)$$

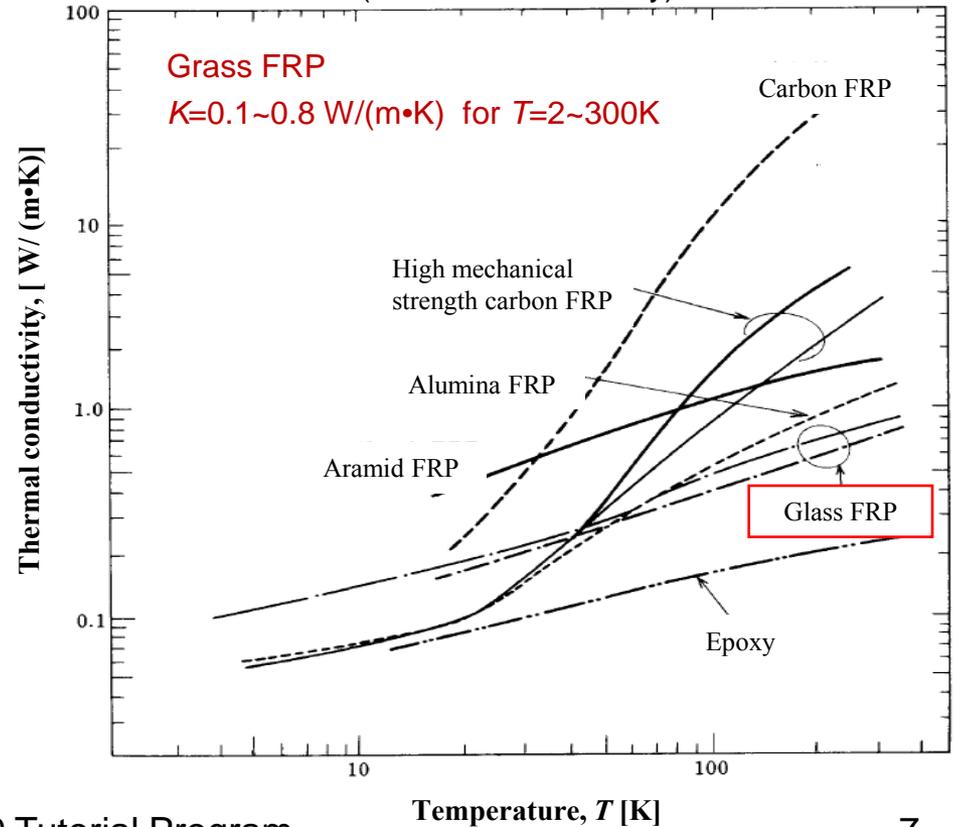
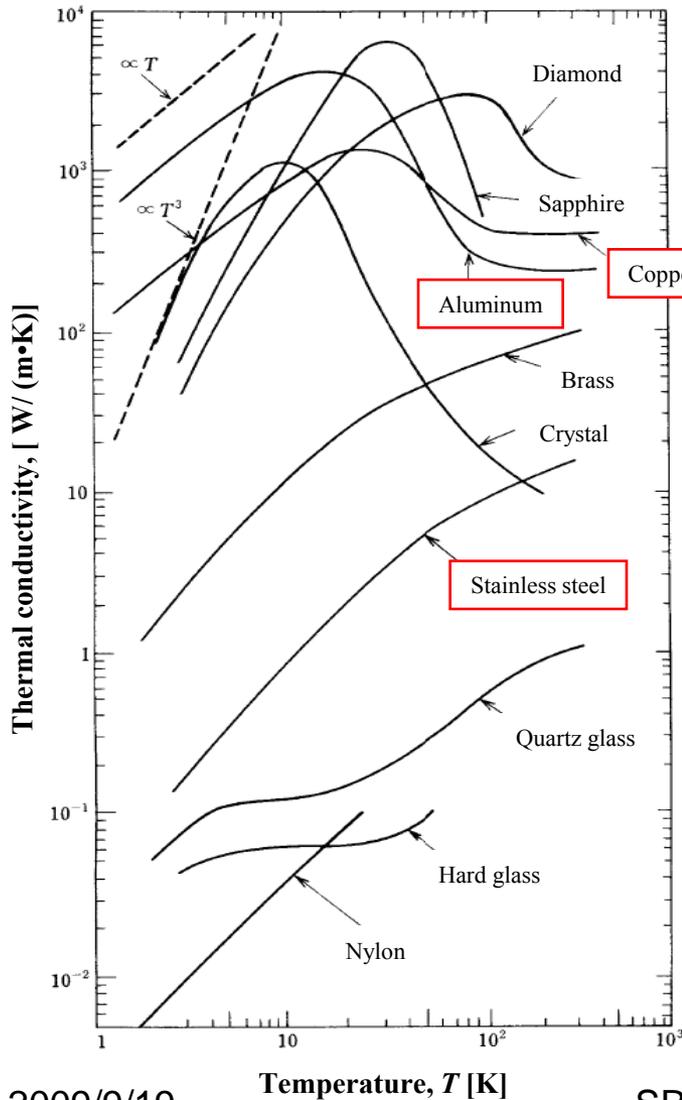
$K$ : thermal conductivity,  $A$ : cross section area

For example of  $A=1 \text{ cm}^2$ ,  $T=300\text{K}\rightarrow 2\text{K}$ ,  $x=20 \text{ cm}$ ,

Cu  $q= 81.0 \text{ W}$

SUS  $q= 1.53 \text{ W}$

Thermal property of cryomodule components  
(Thermal conductivity)

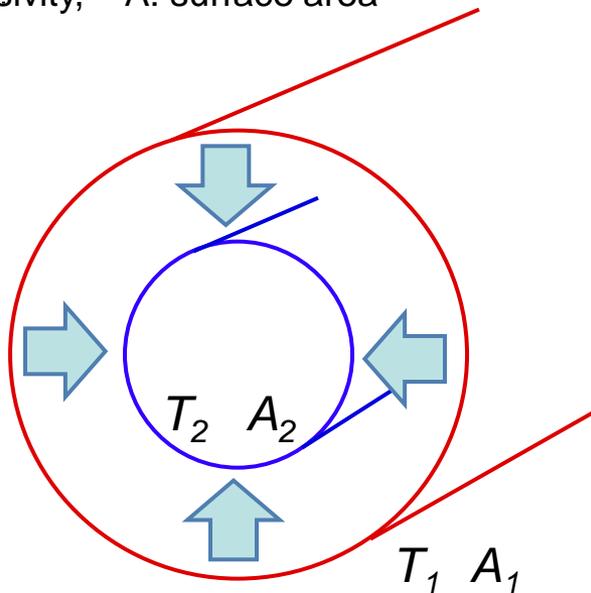


# Heat transfer by thermal radiation

Heat flux by thermal radiation between the coaxial cylinders

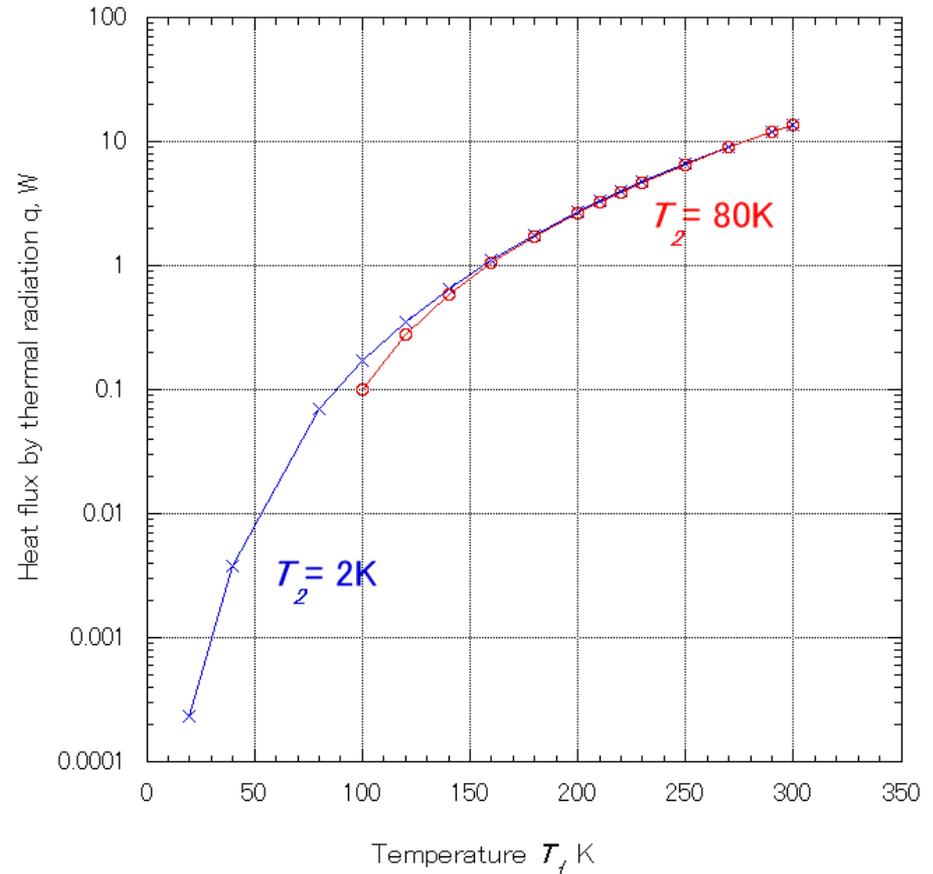
$$q = \frac{\sigma A_1 (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2} \left( \frac{1}{\varepsilon_2} - 1 \right)}$$

$\sigma$  : Stefan-Boltzmann constant =  $5.669 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ ,  
 $\varepsilon$  : emissivity,  $A$  : surface area



Thermal radiation model: coaxial cylinder

For example of  $A_1 = 2 \text{ m}^2$ ,  $A_2 = 1 \text{ m}^2$  cylinder  
 $T_2 = 2 \text{ K}$  and  $80 \text{ K}$ , cylinder material = SUS,  
 $\varepsilon_1 = 0.12$  ( $T > 77 \text{ K}$ ),  $\varepsilon_1 = 0.074$  ( $T < 77 \text{ K}$ )

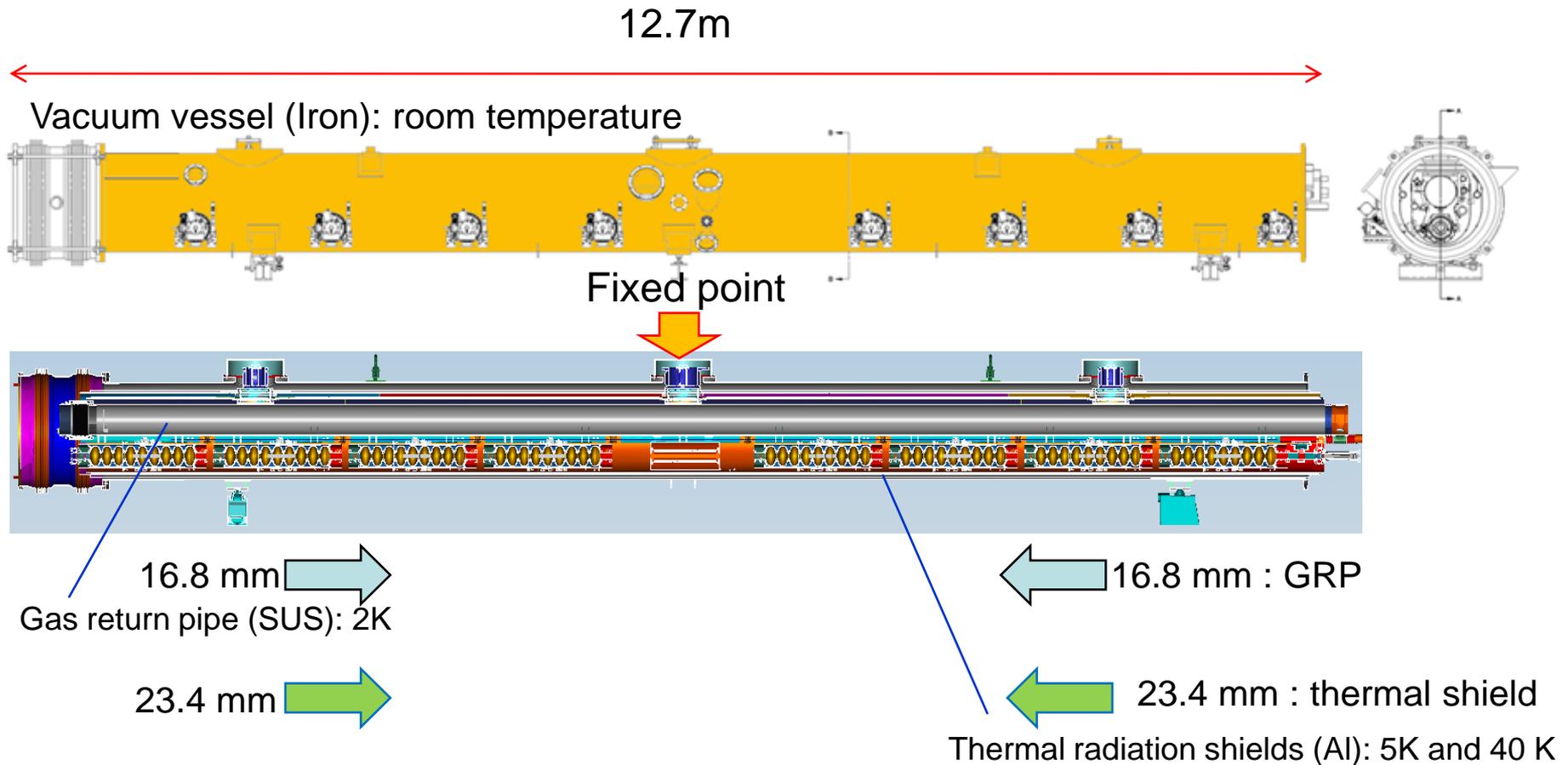


# Estimated heat load for one ILC cryomodule

	2K		5-8K		40-80K	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
RF load		7.5				
Thermal radiation	0.0		1.4		32.5	
Supports	0.6	0.0	2.4		6.0	
Input coupler	0.5	0.2	1.5	1.3	15.5	66.1
HOM coupler (cables)	0.0	0.2	0.3	1.8	1.8	9.0
HOM absorber	0.1	0.0	3.1	0.5	3.3	10.9
Beam tube bellows		0.4				
Current Leads	0.3	0.3	0.5	0.5	4.1	4.1
HOM to structure		1.2				
Coax cable (4)	0.07					
Instrumentation tapes	0.07					
Diagnostic cable			1.4		2.8	
Sum	1.7	9.7	10.6	4.2	59.2	90.1

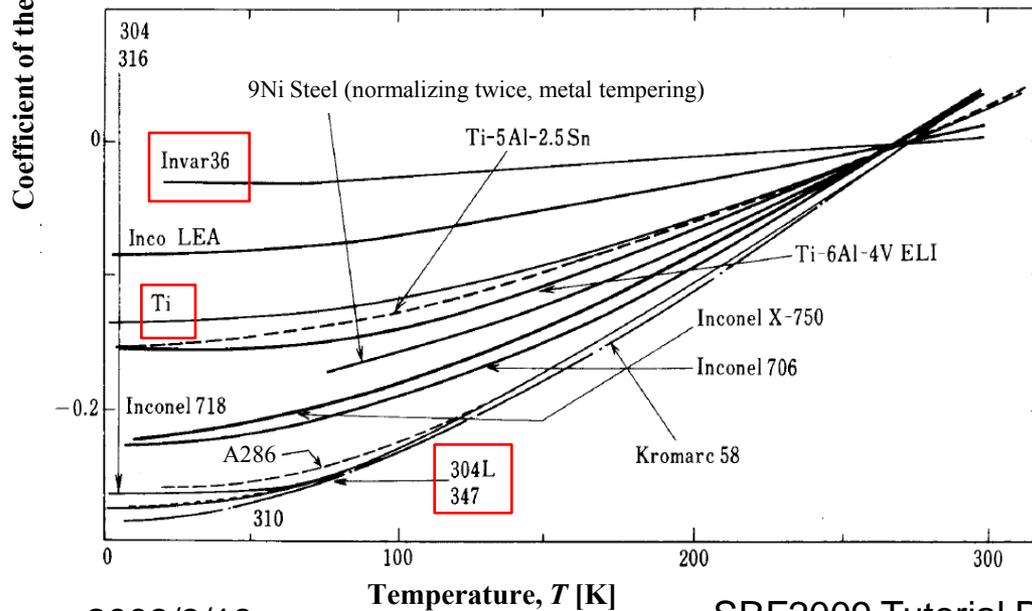
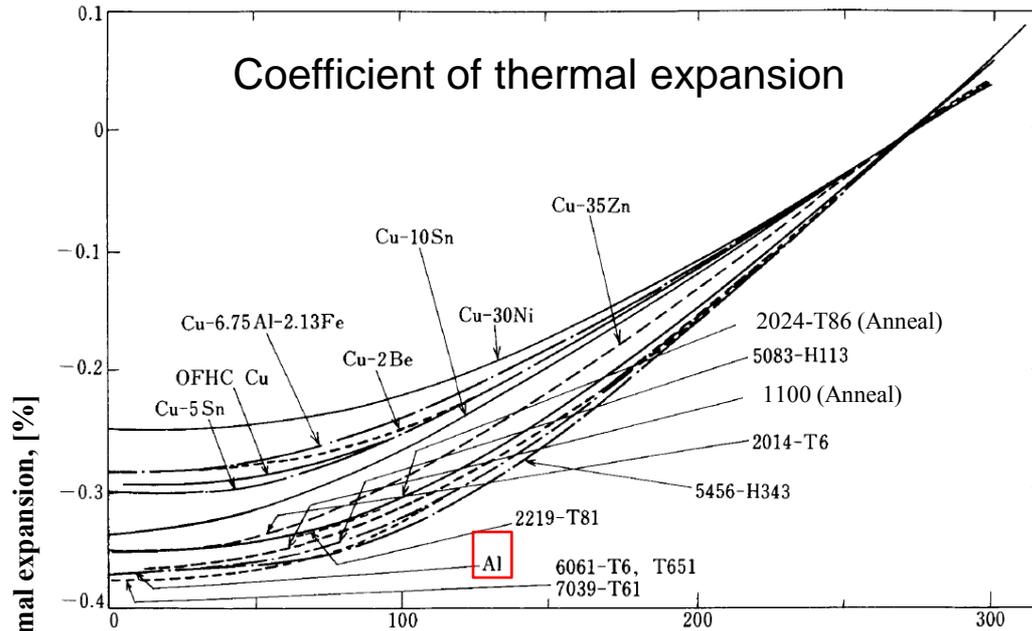
From ILC-RDR

# Thermal contraction of the components of different materials in the module



Pictures from Type-4 cryomodule by FNAL

## Coefficient of thermal expansion



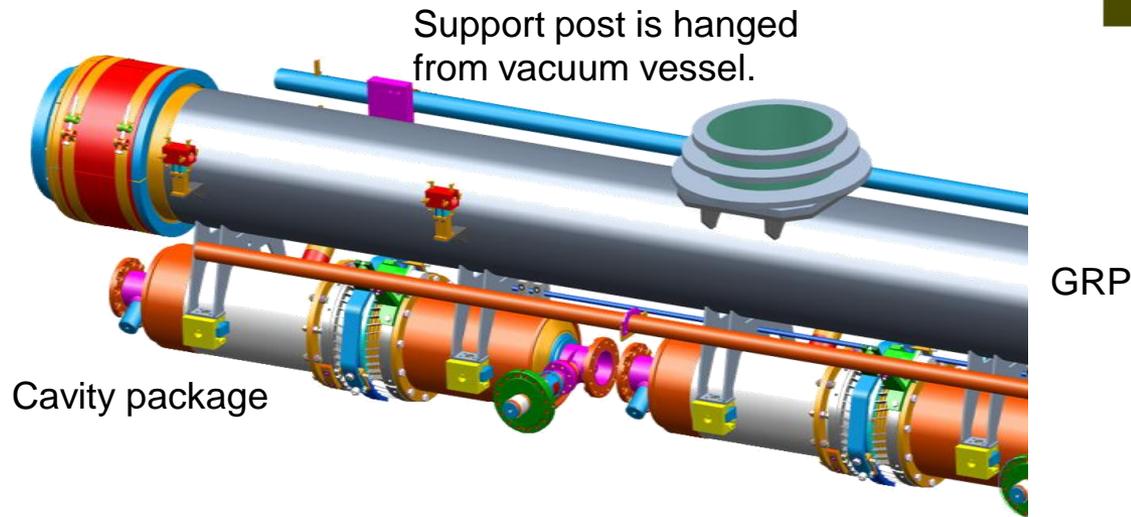
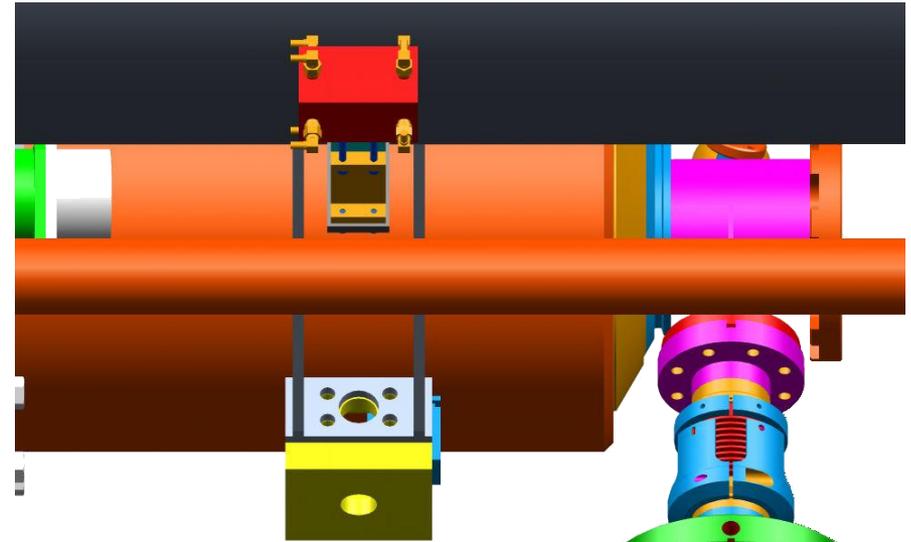
## Thermal property of cryomodule components

### Thermal contraction

Component	Material	Temp.	$\Delta L/L$
Cooling pipes	SUS	300K – 4K	-0.265%
Thermal shields	AL	300K – 4K	-0.368%
Support post	G-FRP	300K – 4K	-0.338%
Cavity	Nb	300K – 4K	-0.129%
Cavity jacket	Ti	300K – 4K	-0.134%
Cavity fixture rod	Invar	300K – 20K	-0.034%

# Supporting cavities in the cryomodule

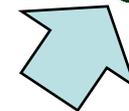
- Cavity jackets are supported from the GRP of  $\phi 300\text{mm}$ .
- The GRP is supported with three support posts from the vacuum vessel.
- The power input couplers are connected between the cavity jacket/beam pipe and the vacuum vessel.



Support post is hanged from vacuum vessel.

Cavity package

GRP



The input coupler flange is connected to the vacuum vessel.

Pictures by Don Mitchell, FNAL

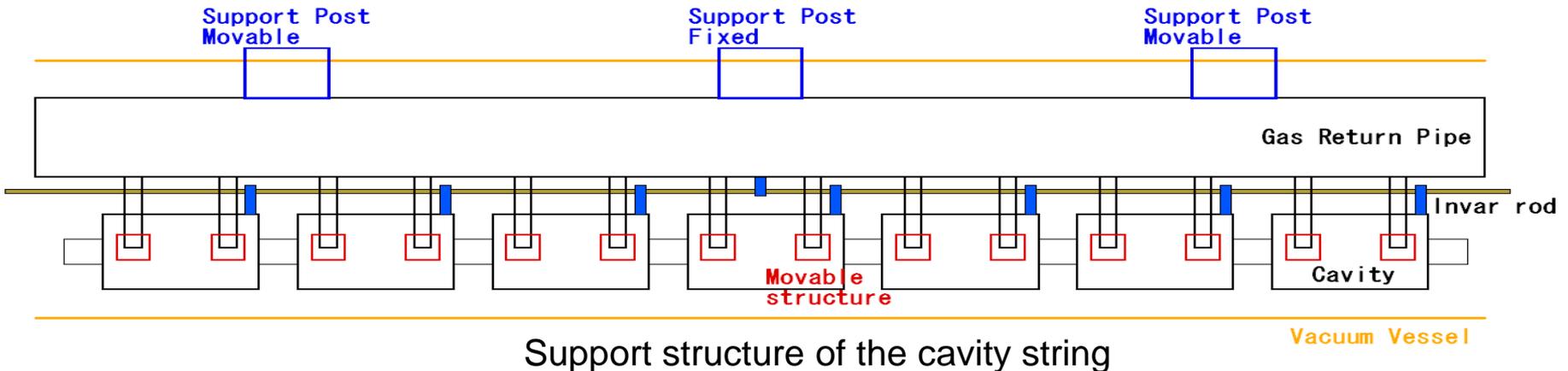
# Supporting cavities in the cryomodule

- By cooling the GRP from room temperature to 2K
  - Thermal contraction (300k-> 2K) = 0.265%
  - Thermal contraction of 12 m gas return pipe= 32 mm
- The cavities locates in the ends of the cryomodule move over 10 mm without any slide mechanism with respect to the vacuum vessel.
  - Risk of damage of the input power coupler.
  - Requirement of sliding structure for the cavity jacket against the thermal contraction of GRP during cool-down and warm-up.

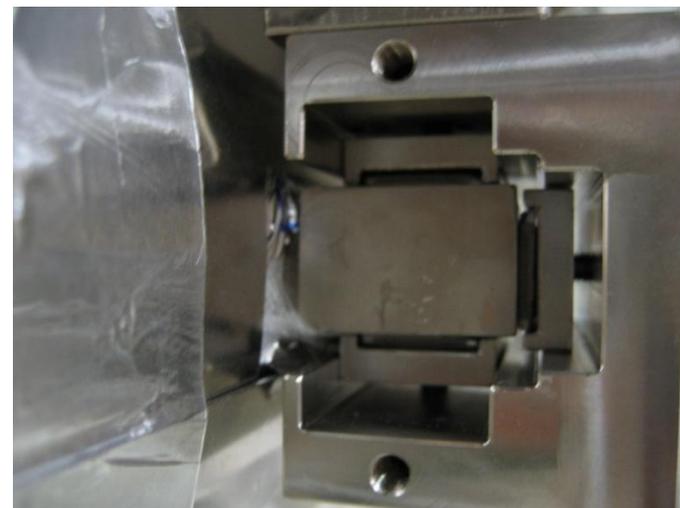
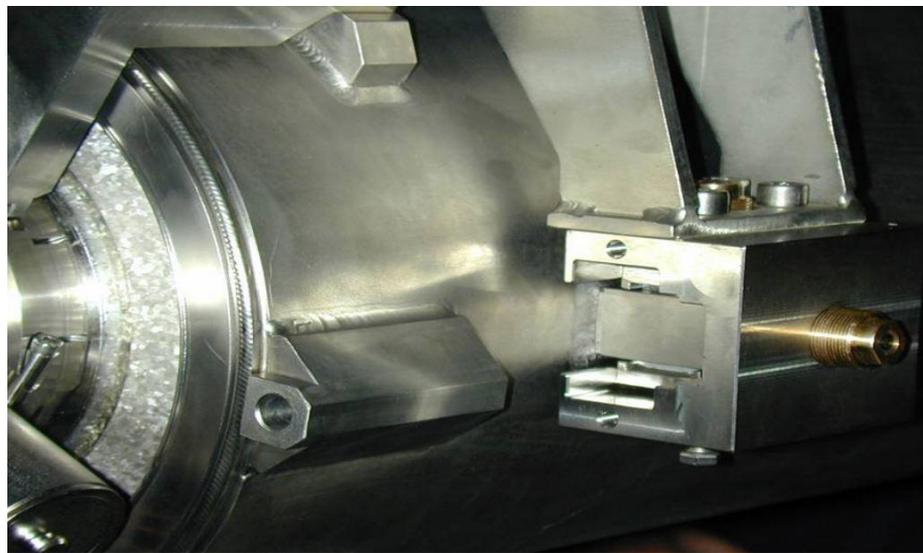
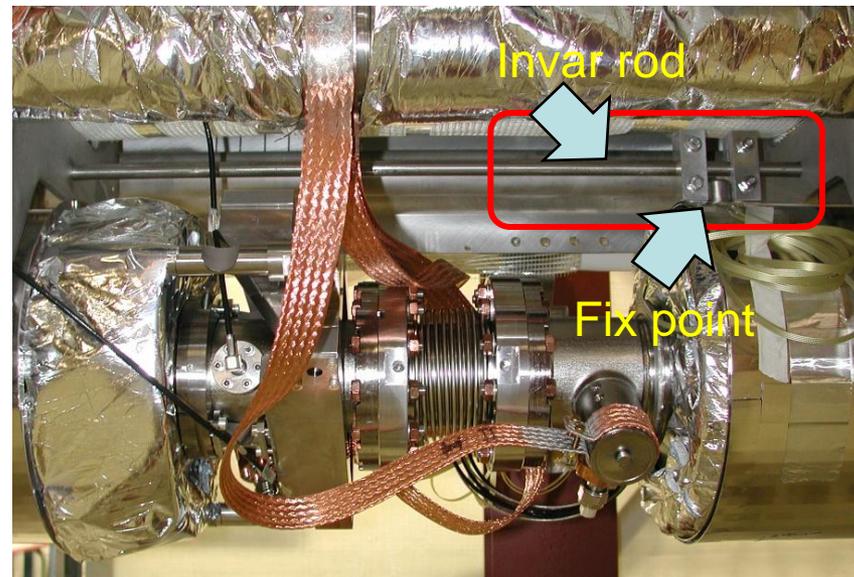
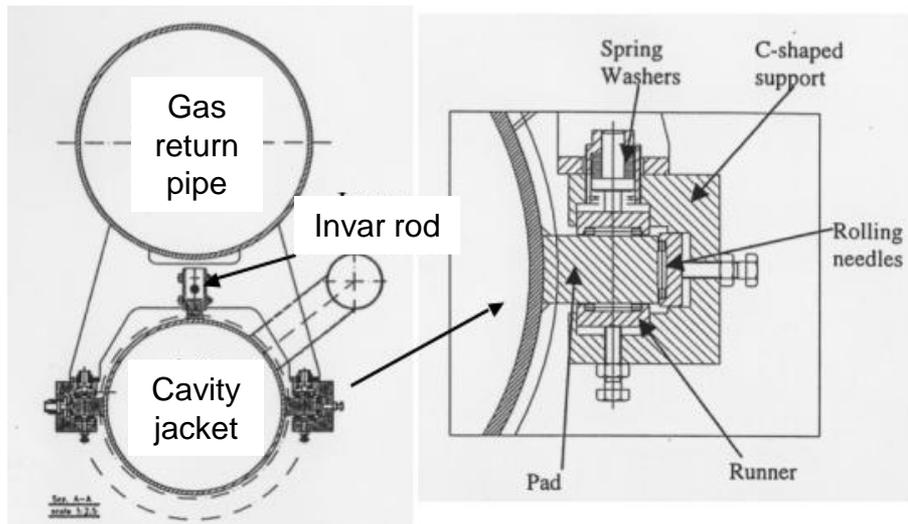
Location change from the module center at 2K

No. of cavity jacket	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>	C <sub>4</sub>	C <sub>5</sub>	C <sub>6</sub>	C <sub>7</sub>	C <sub>8</sub>
Position @ 300K	5693	4312	2929	1547	165	1217	2599	3981
Position @2K	5678	4301	2921	1543	165	1214	2592	3970
$\Delta L$	15.1	11.4	7.8	4.1	0.4	3.2	6.9	10.5
$\Delta L_{in}$	1.9	1.5	1.0	0.5	0.1	0.4	0.9	1.4

- Using an Invar rod for minimizing position change of cavity jackets during cool-down and warm-up.
  - Thermal contraction of Invar =0.034%



# Supporting cavities in the cryomodule

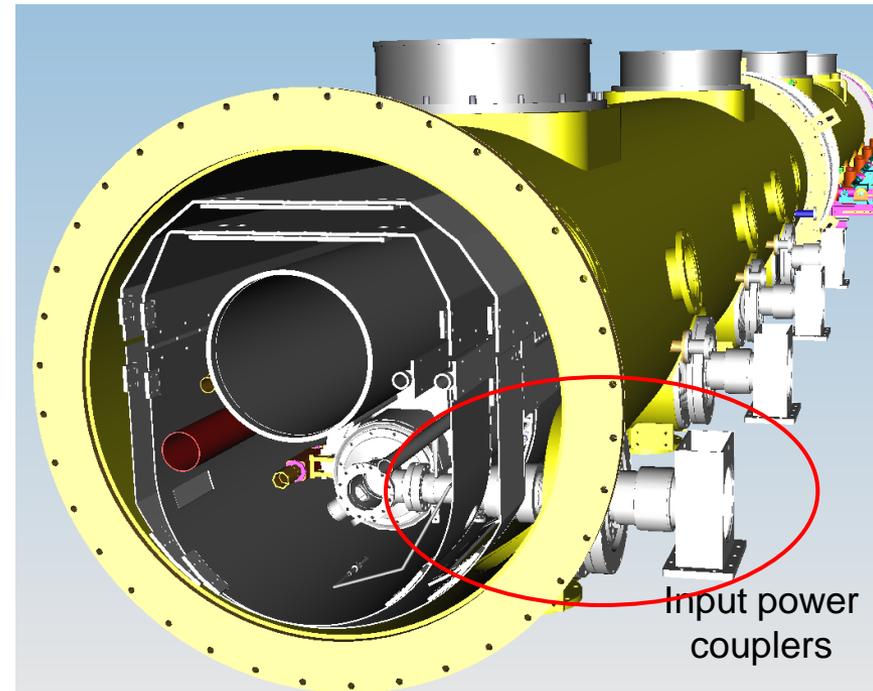
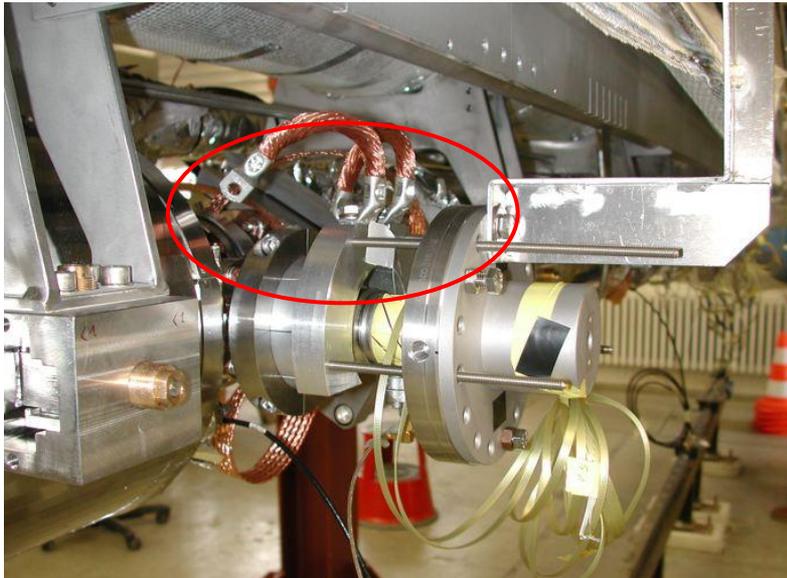


# Cavity component: input power coupler

- Power coupler
  - Supply RF energy to cavities for accelerating a beam.
  - The power coupler connects directly cold parts to the vacuum vessel at room temperature.
  - Conductive heat load from 300K is removed by thermal intercepts connected with 5K and 80 K shields and cooling pipes.

Heat load of power coupler for DESY cavity  
(one component)

	80K	5K	2K
Static [W]	1.78	0.17	0.06
Dynamic [W]	7.60	0.15	0.02
Total [W]	9.38	0.32	0.08



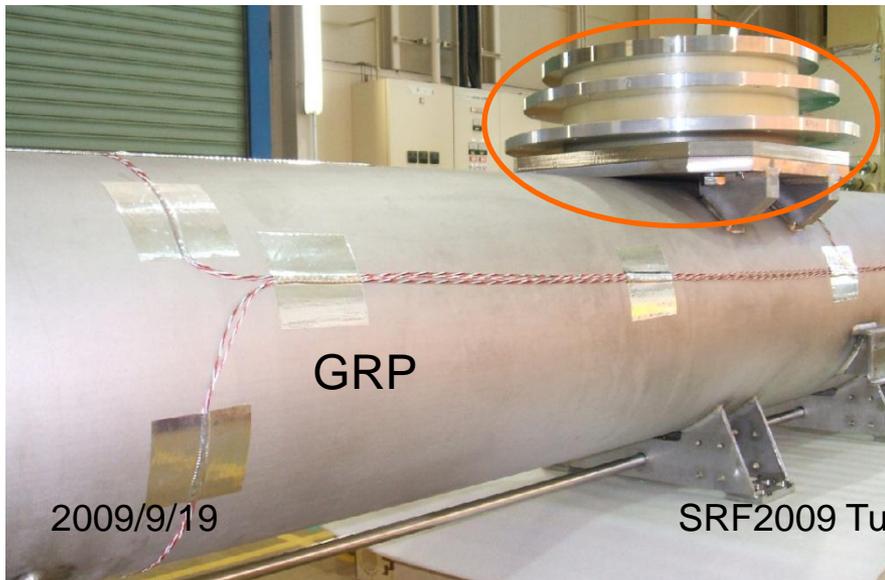
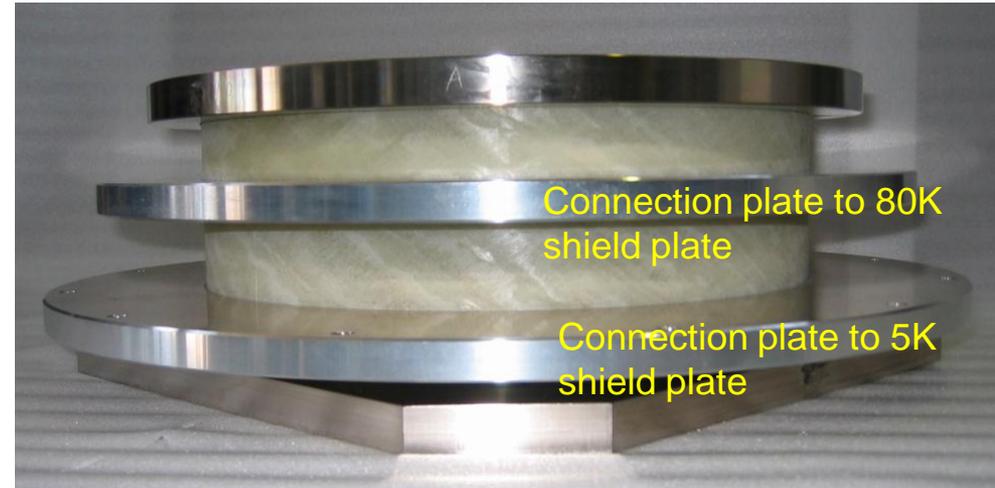
Thermal intercepts for cold coupler  
2009/9/19

KEK-STF cryomodule and power couplers  
SRF2009 Tutorial Program

# Support post-1

- Three G-10 posts for one cryomodule hold 8 cavity jackets, a quadrupole, cooling channels and thermal shields from the vacuum vessel.
  - Weight load for one post is 750 kg.
- The center post in the module is fixed to the vacuum vessel, and the posts in the both ends have a sliding structure for removing the effect of thermal contraction of GRP.
  - Distance changes of posts of the both ends: 12.9mm, 13.2mm.

G-10 support post



# Support post-2

- Thermal design of support post
  - Positions of the thermal intercepts are calculated in order to minimize the heat load to the helium refrigerator.
  - Estimation of the refrigerator load: Carnot efficiency and mechanical efficiency (experimental value)

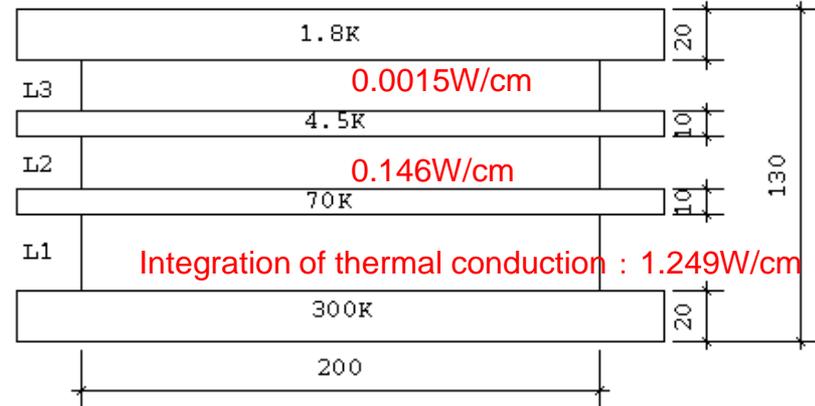
$$\text{Carnot efficiency} = T_c / (T_o - T_c)$$

- Optimization by the distance of L2
- Calculation result
  - L<sub>2</sub> distance : Refrigerator heat load is minimized at 50% of the total conductive length of the post.
  - The heat load is not sensitive to the value of L<sub>2</sub>.
- Designed post
  - Post height: 140mm, L<sub>1</sub>=27mm, L<sub>2</sub>=37mm, L<sub>3</sub>=10mm
  - G-10 pipe: Outer diameter=300mm, thickness=2.2mm,
- Heat load
  - 0.1W @ 2.0K, 0.65W @ 5K, 5.9W @ 70K
  - Required work for refrigerator : 473 W/W

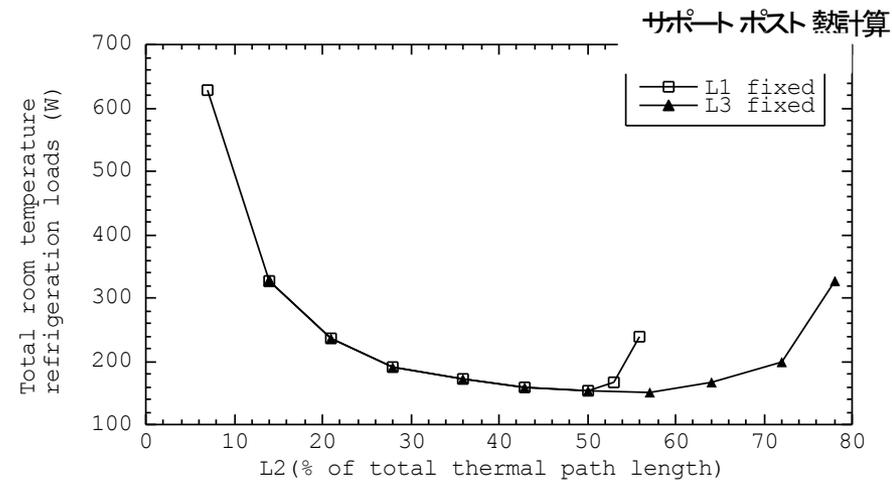
Required work for refrigerator at room temperature

Temp.	Carnot efficiency	Mechanical efficiency	Total efficiency	Required work at 300K W/W
70K	30.43%	20%	6.09%	16
4.5K	1.52%	20%	0.30%	328
1.8K	0.60%	10%	0.06%	1657

Thickness of G-10 pipe: 1mm



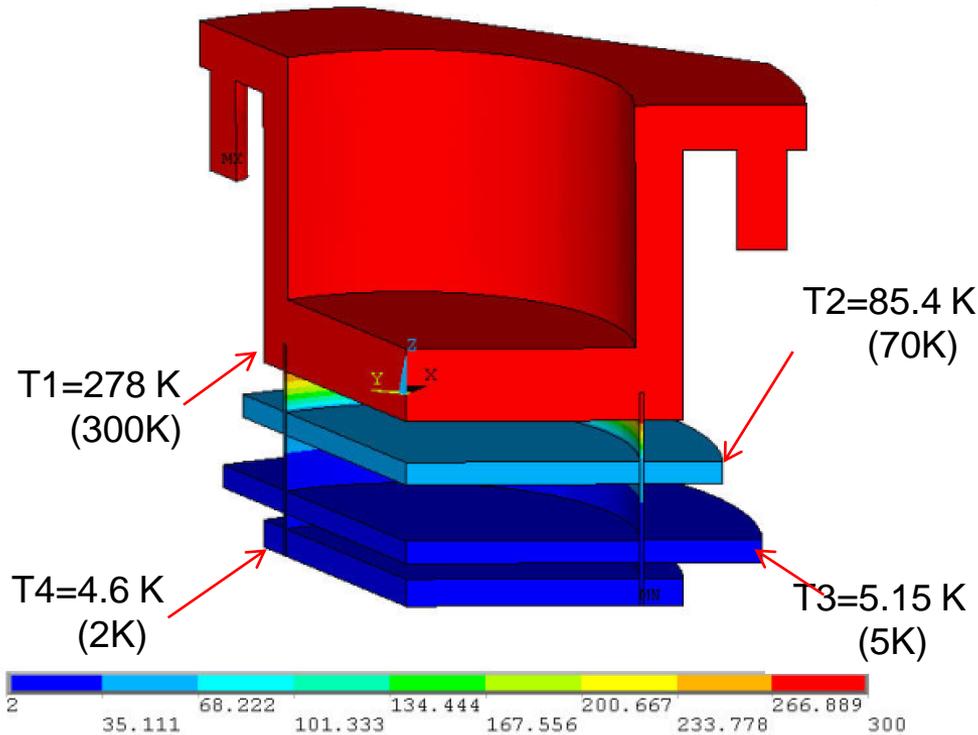
Thermal analysis model of support post



Effect of the thermal intercept position on the heat load to the refrigerator

# Support post-3

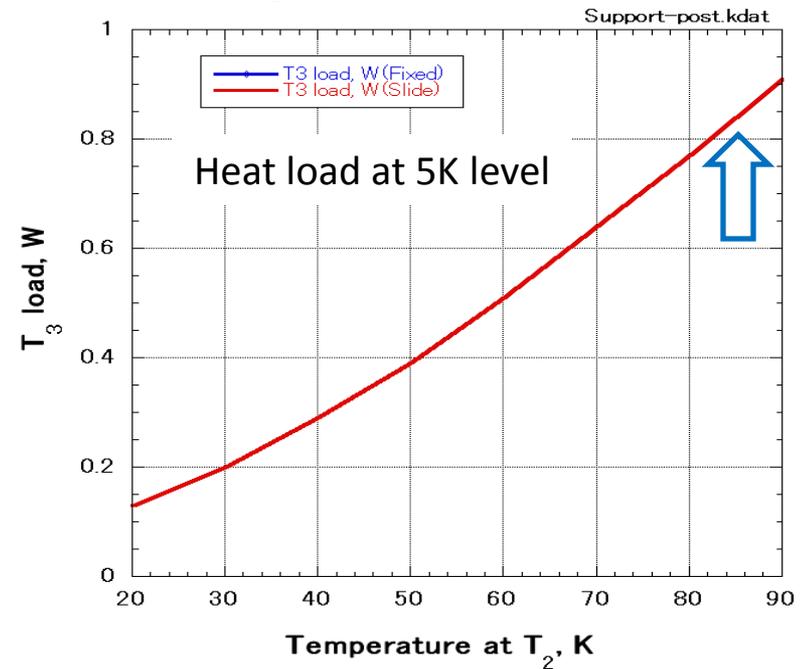
(Thermal calculation by FEM and measured temperatures)



GRP upper surface = 3.82 K  
GRP lower surface = 2.02 K

Condition of the calculation

- $T_1 = 300\text{K}$ ,  $T_3 = 5\text{K}$ ,  $T_4 = 2\text{K}$  (Fixed)
- $T_2 =$  parameter for calculation



$T_2=85.4$  K  
80 K : 5.4 W  
5 K : 0.85 W  
2 K : 0.12 W

# Thermal radiation shields -1

- Constitution of thermal radiation shields
  - Aluminum plate cooled at 5K and 80K
    - Area of 5K shield plate=30m<sup>2</sup>
    - Area of 80K shield plate=35m<sup>2</sup>
  - Multi-layer insulation of aluminum-evaporated film (Super insulation: SI)
    - 10 layers of SI on 5K aluminum plate
    - 30 layers of SI on 80K aluminum plate
  - Aluminum-evaporated film
    - Polyester film of 6~25 micro-meter thickness with evaporated aluminum of 0.1 micro-meter thickness
    - Emissivity :  $\epsilon=0.056$  (80K~300K),  $\epsilon=0.011$  (4.2K~80K)

Heat transfer by thermal radiation between the parallel plates

$$Q_r = A\sigma \left( \frac{1}{1/\epsilon_h + 1/\epsilon_c - 1} \right) (T_h^4 - T_c^4)$$

A: area,  $\sigma$ : Stefan-Boltzmann constant,  $\epsilon$ : emissivity,  
h: high temperature, c: low temperature

Thermal radiation shield plate at 80K



Assembly of thermal radiation shields at DESY



# Thermal radiation shields -2

- The experimental data in CERN-LHC is used for calculating the effective heat load by thermal radiation:

- Heat flux to 70 K shields from 300 K with 30 layers of SI:  $1\sim 1.5 \text{ W/m}^2$
- Heat flux to 5K shields from 70K with 10 layers of SI:  $0.05 \text{ W/m}^2$

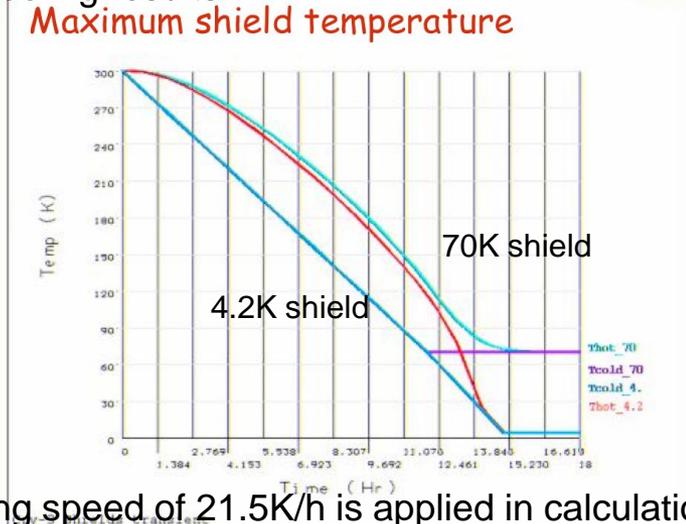
## Heat load by thermal radiation (calculation)

	With SI	Without SI
300K->80K heat flux, W/m <sup>2</sup>	1~1.5	45.7
300K->80K total heat load, W	35~53	1600
80K->5K heat flux, W/m <sup>2</sup>	0.05	0.232
80K->5K total heat load, W	1.5	6.96

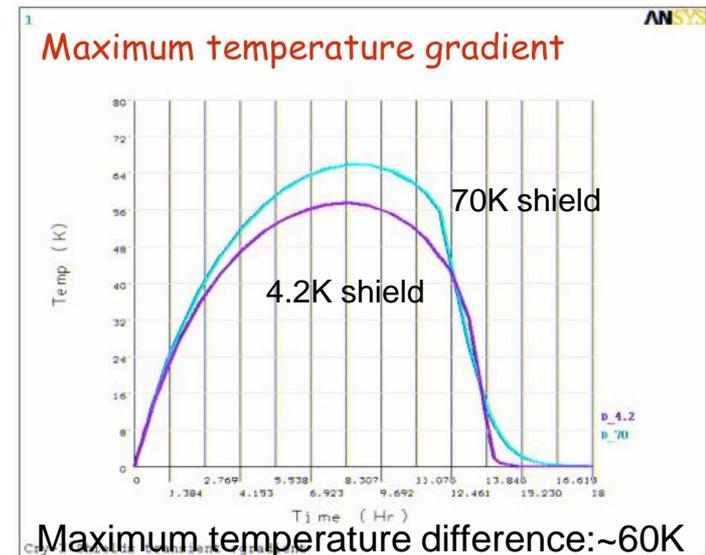
Emissivity without SI : 0.1

- Temperature profile in the thermal radiation shields
  - During cool-down, the temperature profile is in transient state, and the large temperature difference happens in the shield.(Calculation by INFN Carlo Pagani etc.)

### Cooling results



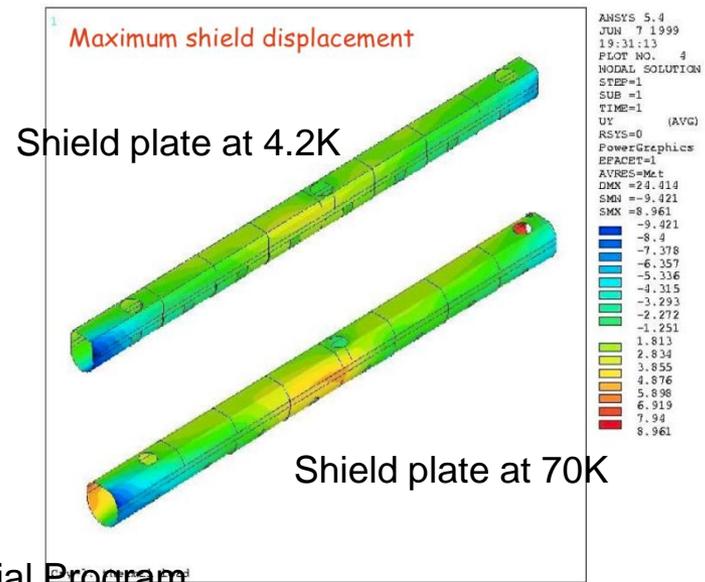
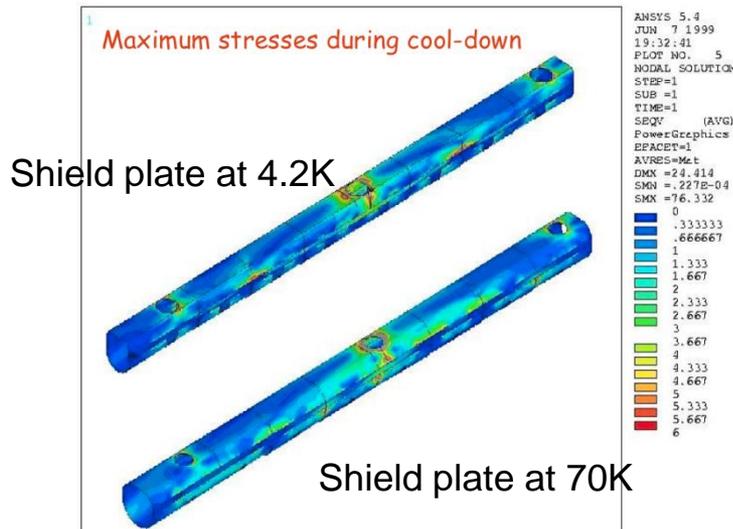
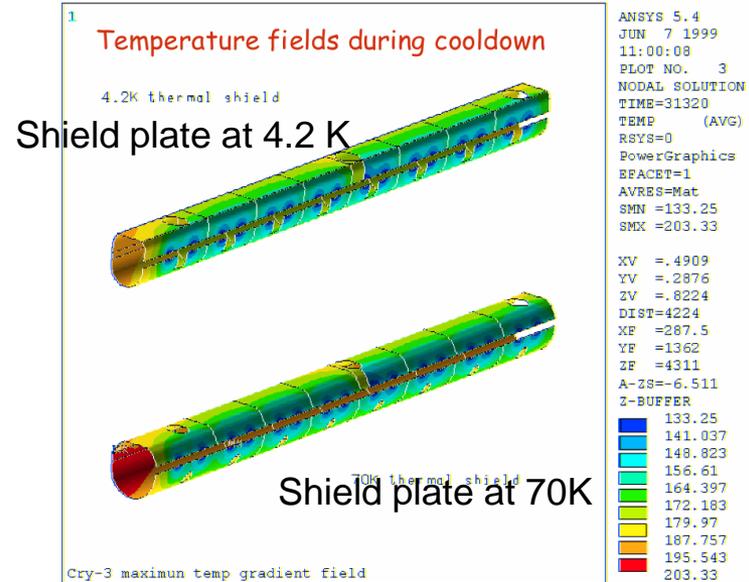
Cooling speed of 21.5K/h is applied in calculation



Maximum temperature difference: ~60K

# Thermal radiation shield-3

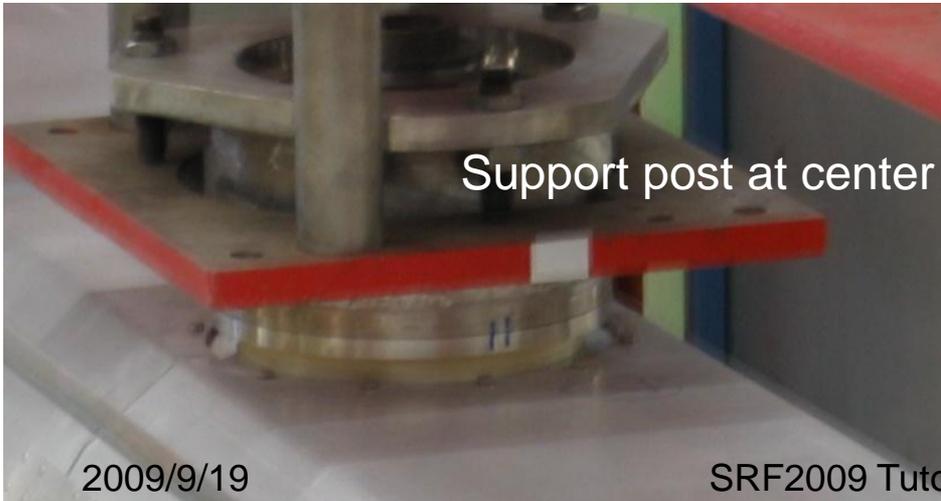
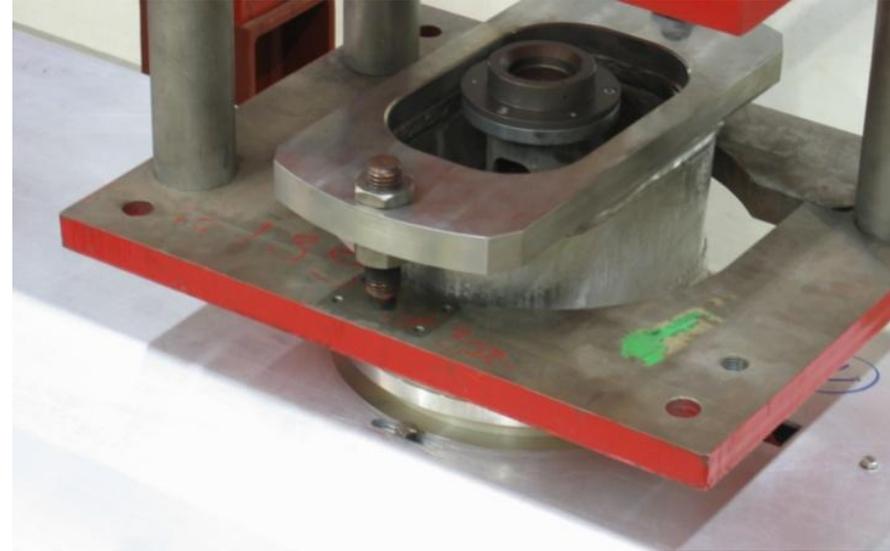
- Temperature profile in the shield plate
  - Calculation result at 8.7 hours after cooling starts
  - The cooling pipe is welded along the one side of shield plate. This side shows lower temperature than the other parts.
- Stress in the shield plate
  - Calculated maximum thermal stress : 30MPa
- Displacement by temperature profile and thermal stress
  - Horizontal direction : ~10mm



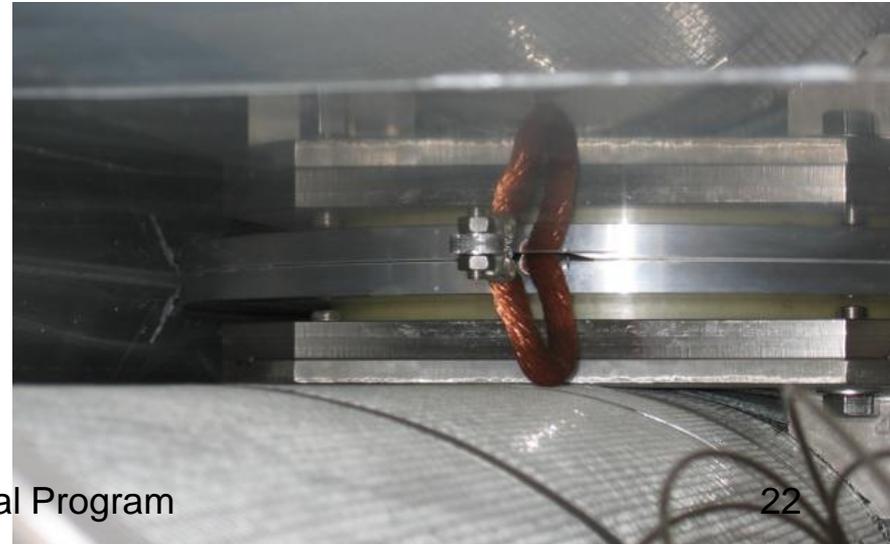
# Thermal radiation shield-4



Support post at both sides

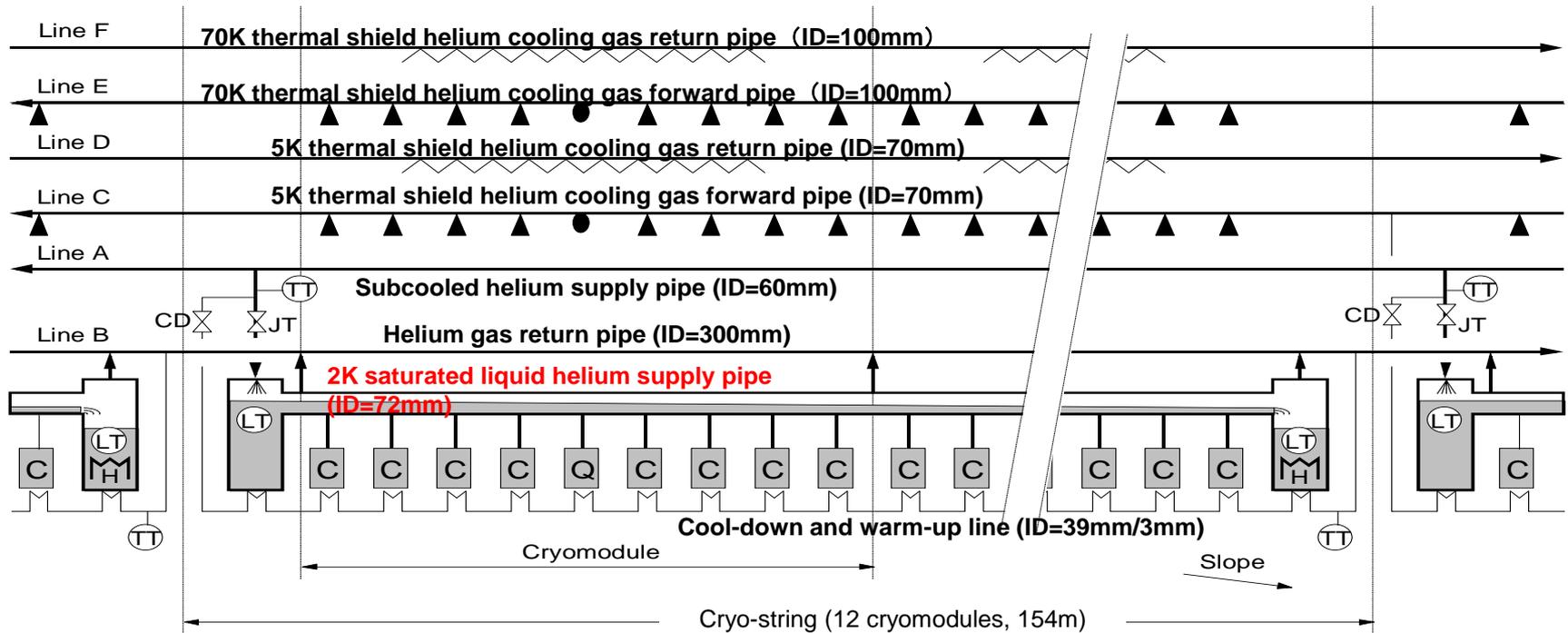


Support post at center



# Cooling pipe (cooling circuit)

- Eight cooling pipes are designed in the cryomodule.
- One cryo-string = 12 cryomodules (154m)
  - Two liquid helium reservoir at both ends for keeping the liquid helium level.
  - The liquid helium level is controlled in the 2K liquid helium supply pipe.
- Saturated pressure liquid helium at 2K ( $P=3.1\text{kPa}$ ) is produced by the adiabatic expansion from sub-cooled liquid helium (2.2K, 0.12MPa).



▲ Coupler & Adsorber heat intercepts

● Current lead heat intercepts

⚡ Screens or shields

□ 9-cell cavities

□ SC quadrupole

⊞ Heater

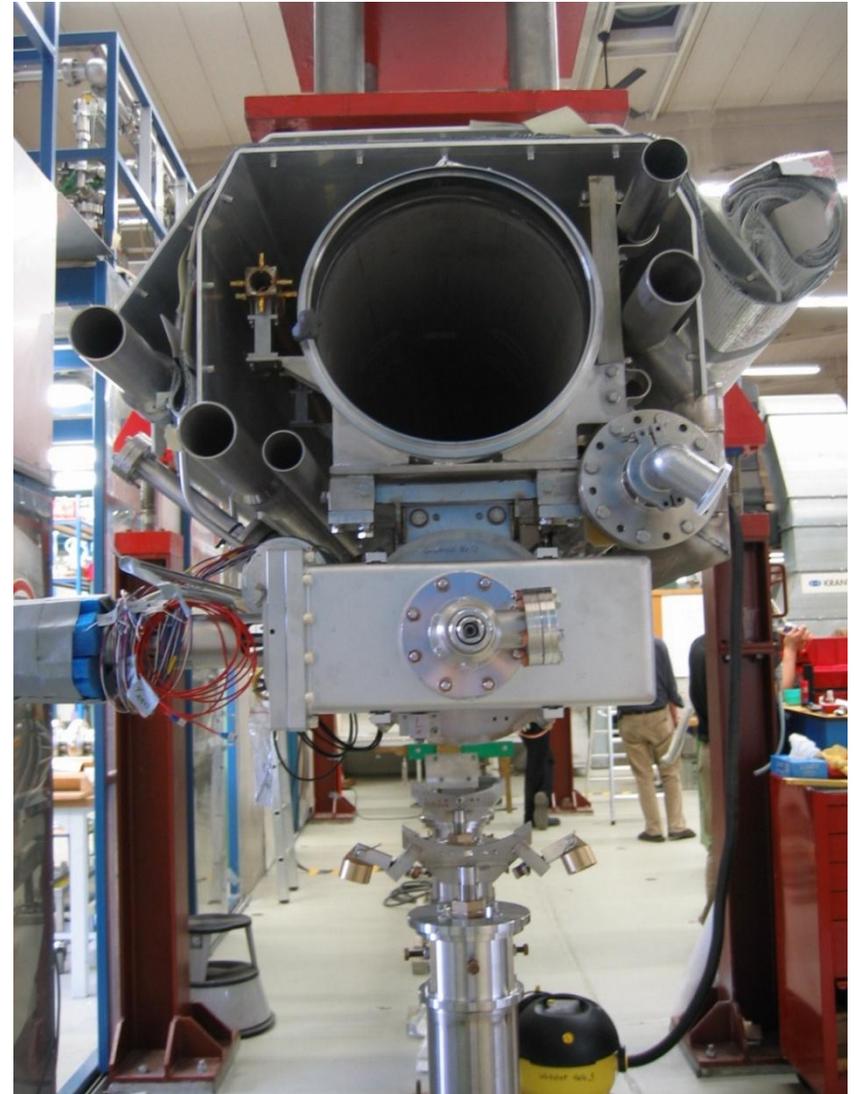
⊞ Temperature sensor

⊞ SC level sensor

# Helium gas return pipe-1

## Function of the helium gas return pipe

1. The cryogenic system including the pump system locates every 2.5 km along the accelerator.
2. Diameter of 300 mm
  - The pressure drop induced by the gas flow of evaporated gas influences the temperature of the saturated liquid helium along the accelerator.
3. 8 superconducting cavities and one superconducting quadrupole are supported from the gas return pipe. (Back bone of the cryomodule)
  - The weight of the cold mass supported by the gas return pipe reaches 2 ton.
  - The sag of the gas return pipe is less than 50 micro meter when this pipe is hanged with three posts.



Cooling pipes in the DESY cryomodule

# Helium gas return pipe-2

(Effect of pressure distribution on temperature profile along the accelerator)

## Condition of the calculation

- Cryomodules locate every 17m along the accelerator of 2.5 km. Total number of cryomodules is 147.
- Heat load of one cryomodule is assumed to be 10W or 30W.

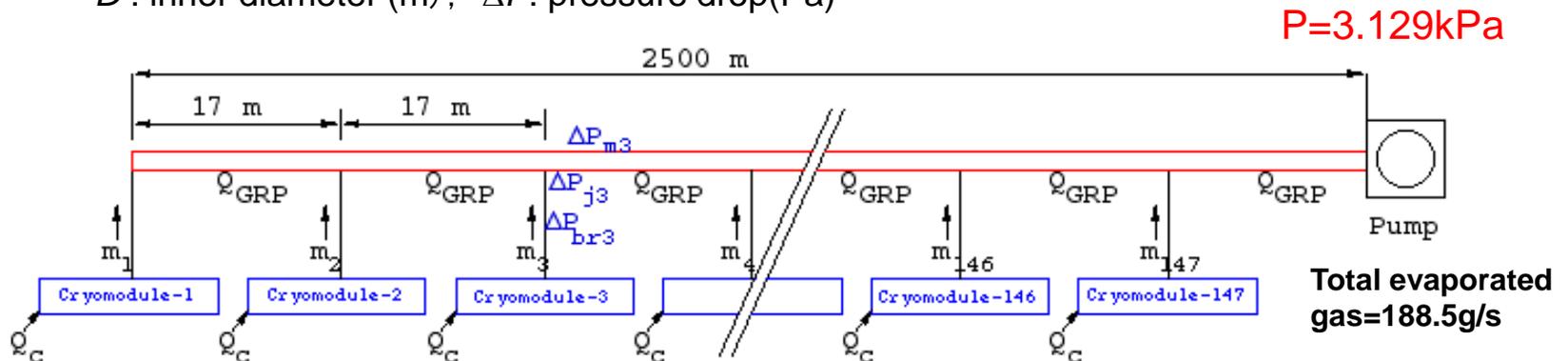
## Equation of pressure drop

$$\Delta P = 4f \times (G^2 / 2\rho) \times (L/D)$$

$f$ : friction factor,  $G$ : mass flow rate (kg/m<sup>2</sup>/s),

$\rho$ : density (kg/m<sup>3</sup>),  $L$ : pipe length (m),

$D$ : inner diameter (m),  $\Delta P$ : pressure drop (Pa)



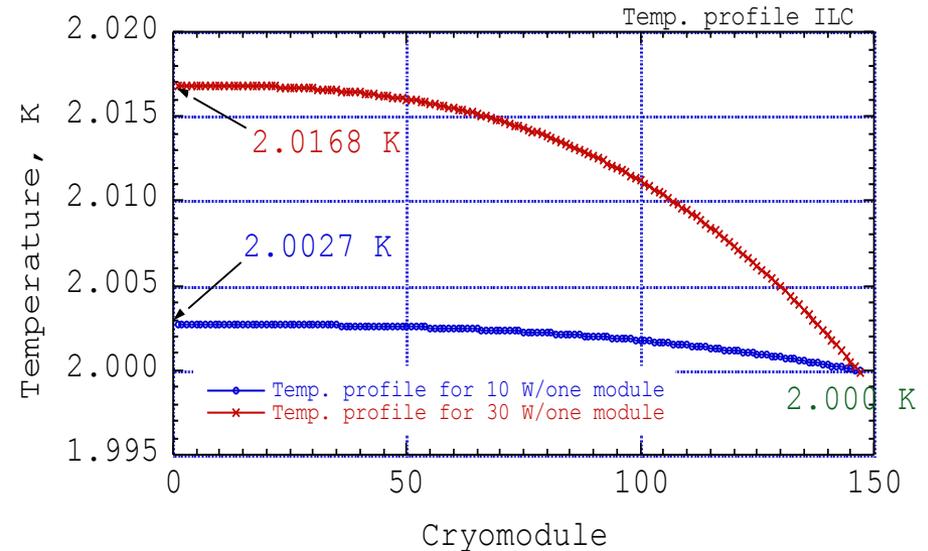
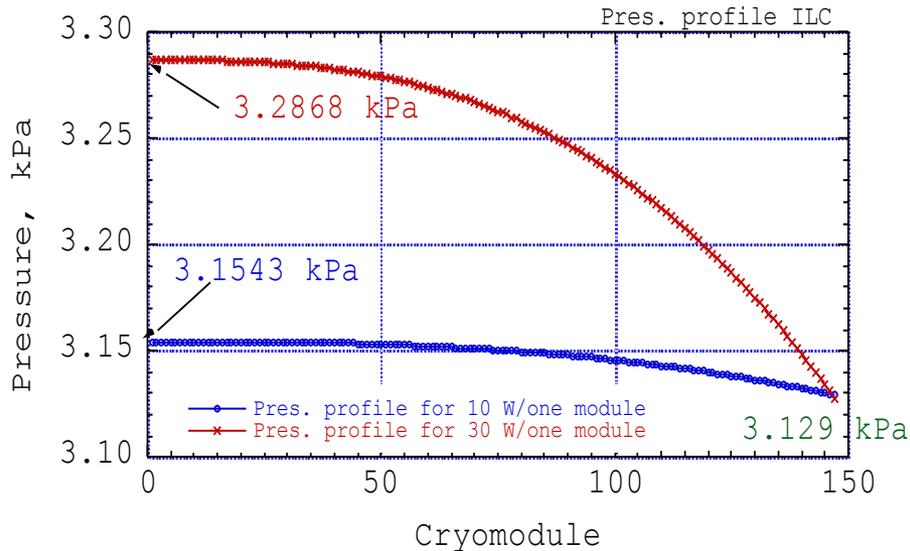
Calculation model of pressure profile by evaporated gas

**Heat load of one module :  $Q_c=10\text{W}$  or  $30\text{W}$**

**Evaporated gas :  $m=0.43 \text{ g/s}$  for  $10\text{W}$  or  $1.28\text{g/s}$  for  $30\text{W}$**

# Helium gas return pipe-3

(Effect of pressure distribution on temperature profile along the accelerator)



- Pressure drop along the 2.5 km GRP = 25 Pa for 10 W, 158 Pa for 30W
- Temperature difference along the 2.5 km GRP = 3 mK for 10 W, 17 mK for 30W

# Assembly of cryomodule in DESY -1

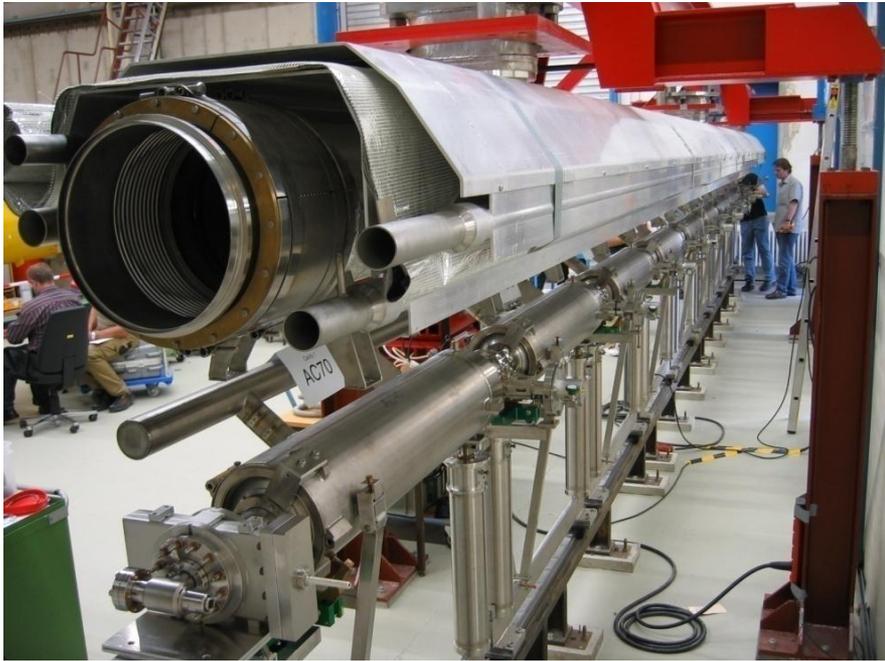


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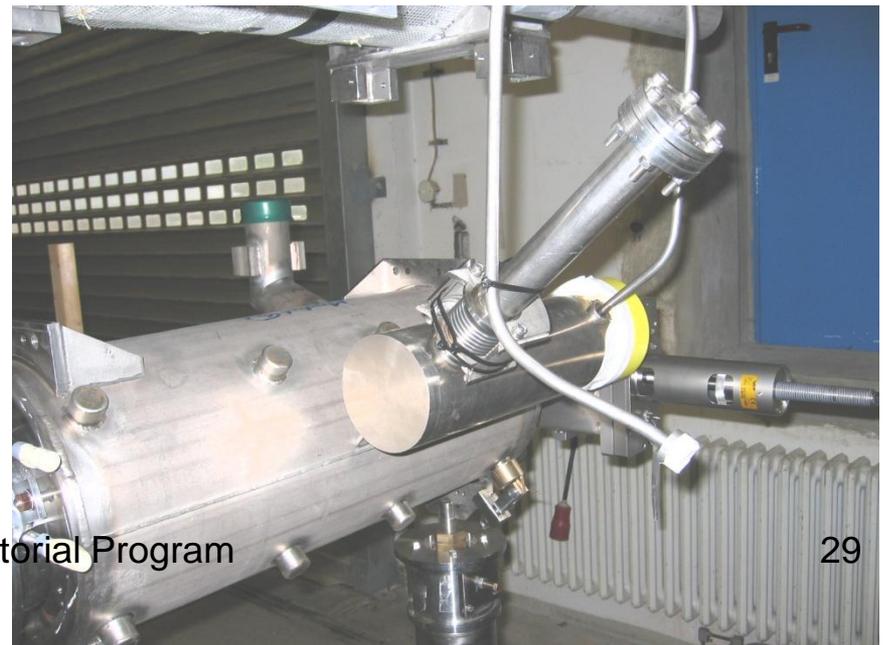
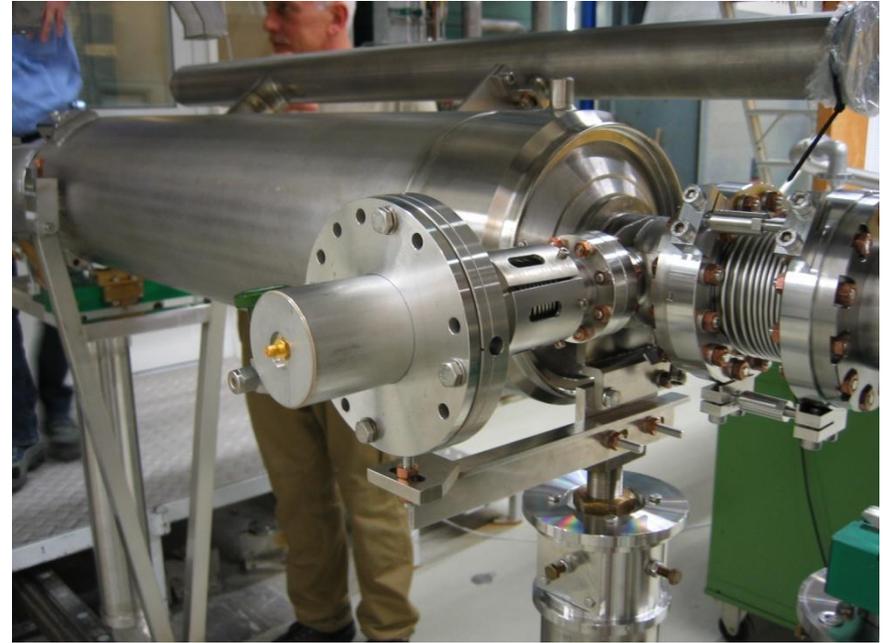
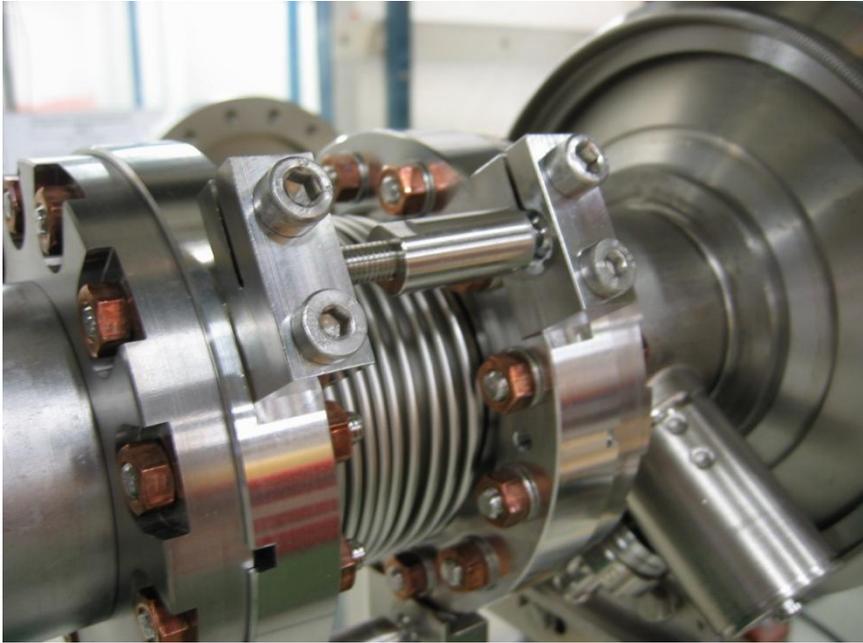
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27

# Assembly of cryomodule in DESY - 2



# Assembly of cryomodule in DESY - 3

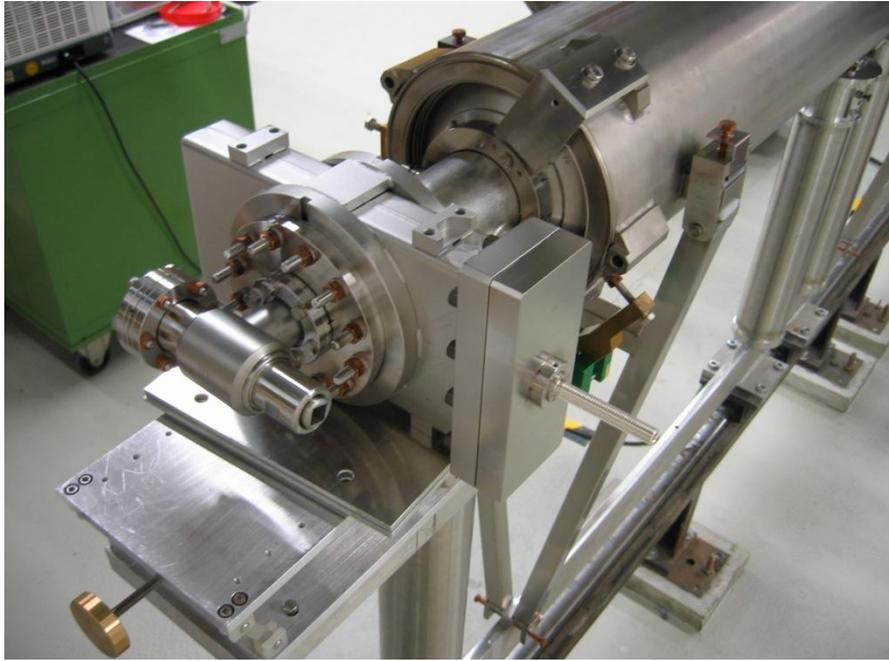


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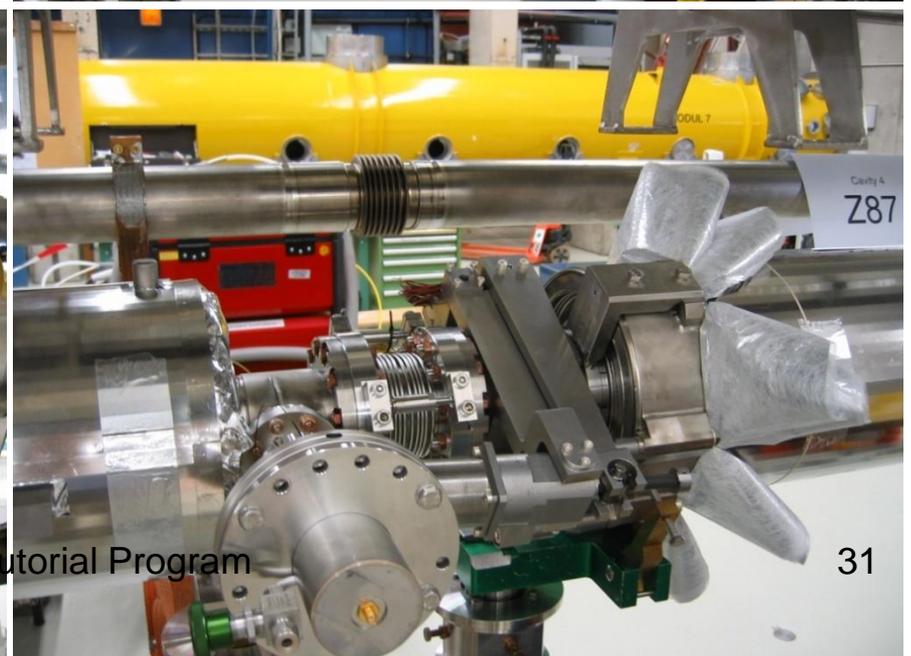
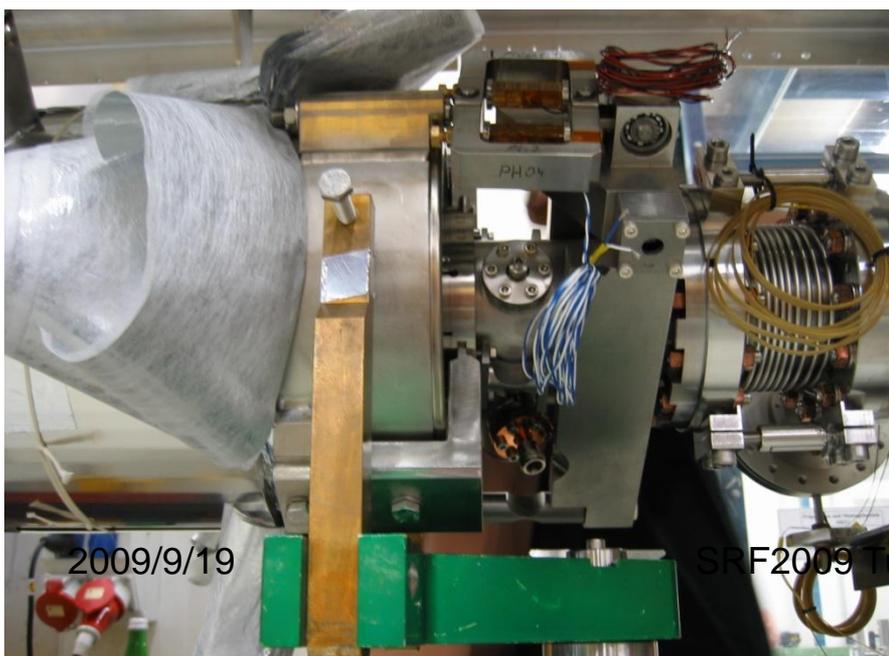
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29

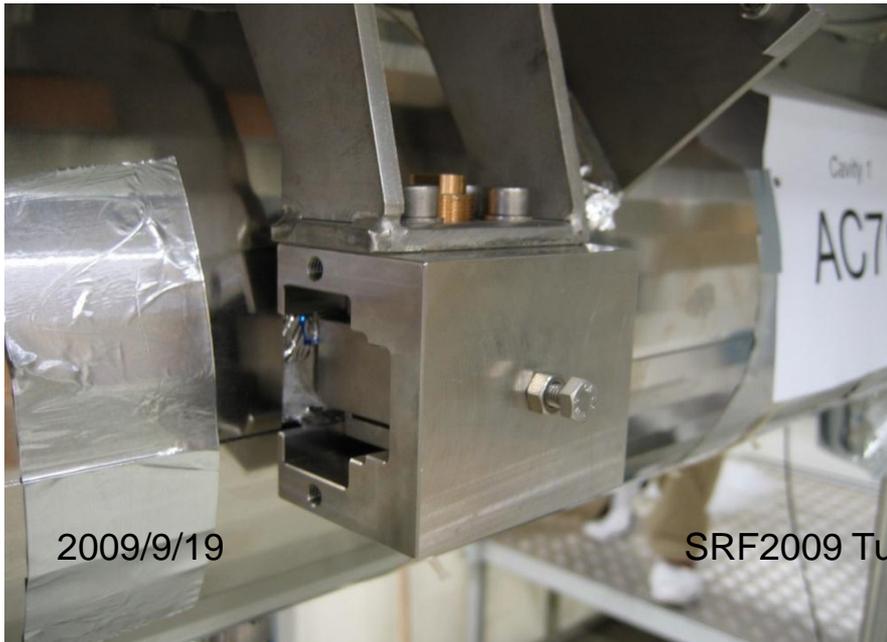
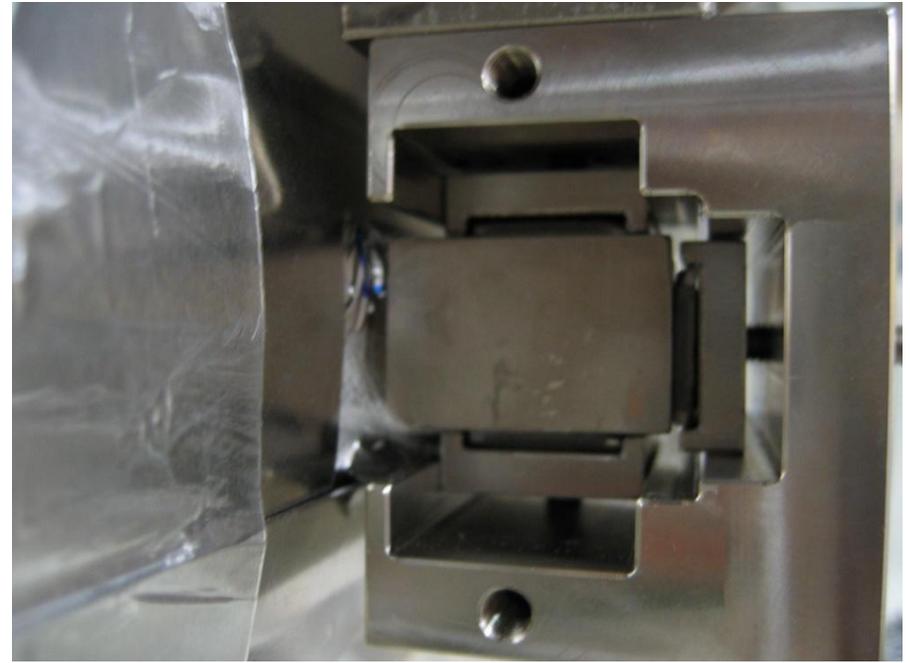
# Assembly of cryomodule in DESY - 4



# Assembly of cryomodule in DESY - 5



# Assembly of cryomodule in DESY - 6



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# Assembly of cryomodule in DESY - 7



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33

# Assembly of cryomodule in DESY - 8



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34

# Assembly of cryomodule in DESY - 9



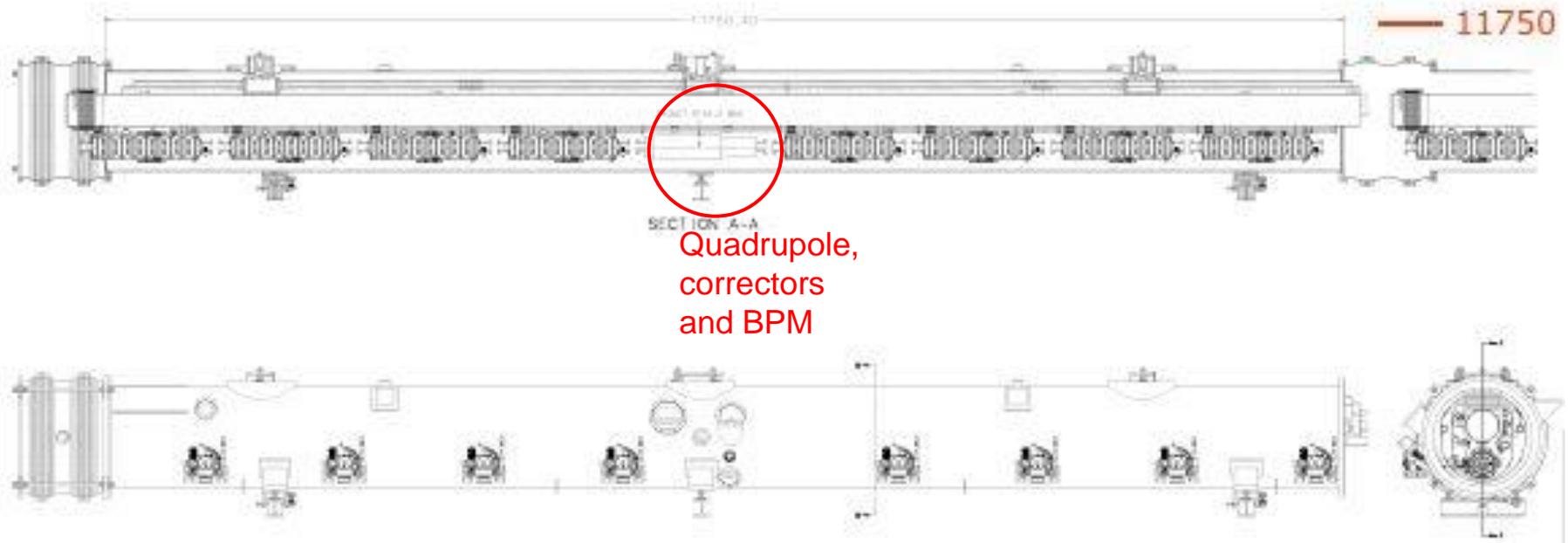
# Summary

## Study items for ILC cryomodule

- The basic function of the cryomodule has been developed by DESY and INFN.
- Improvement of cavity packing factor for increasing the effective field gradient.
- Development and construction of the cryomodule which has the quadrupole/ correctors/BPM in the center of the cryomodule.
- Optimization of the thermal shield system with considering construction and operation cost.
- The vibration of the cavities and the quadrupole in the cryomodule.
- Alignment repeatability of the cavities and the quadrupole after thermal cycle.

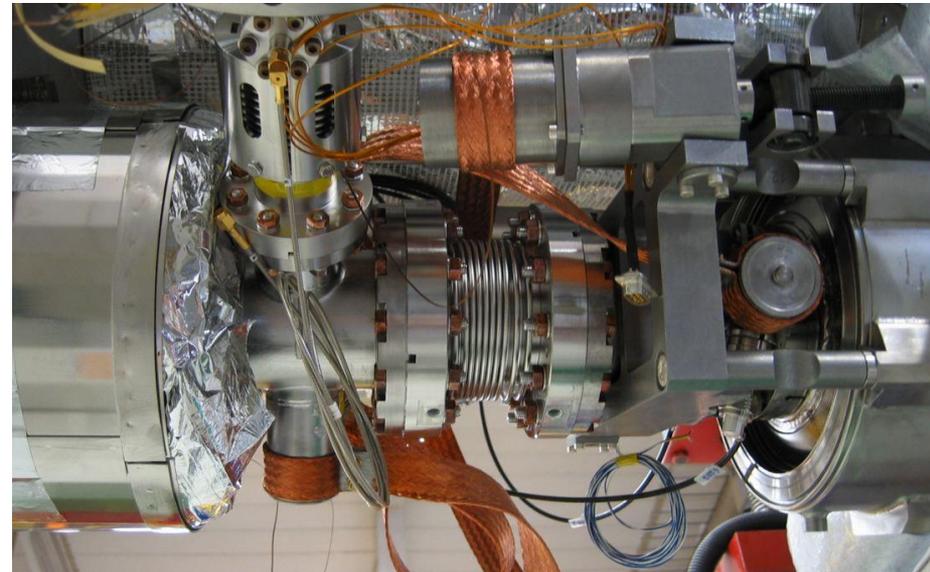
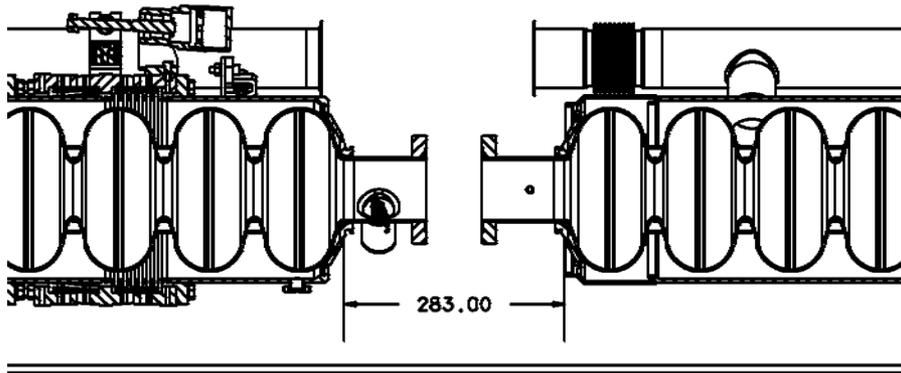
# Improvement of cryomodule for ILC

- The development of the cryomodule which has the quadrupole/correctors/BPM in the center of the cryomodule.
  - In the TESLA and XFEL cryomodules, the quadrupole locates at the end of the cryomodule. In this case, the quadrupole position is influenced by the cooling condition including cool-down and warm-up.
  - The position under the support post at the center is the fixed position in the cryomodule, and it is insensitive to the thermal cycle.



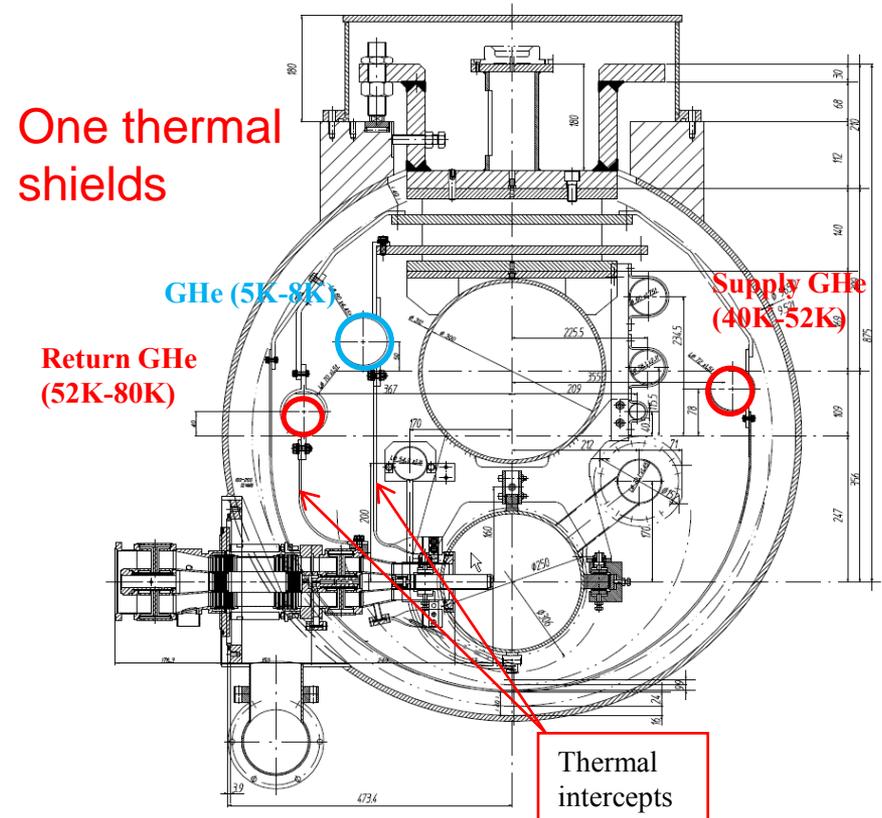
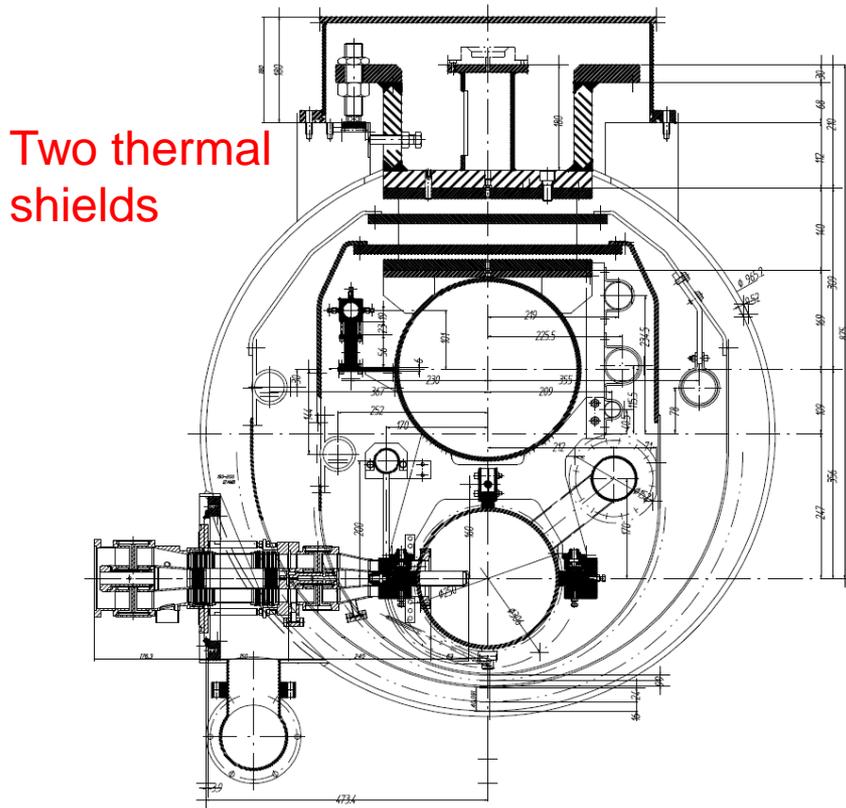
# Improvement of cryomodule for ILC

- Making the distance short between cavities and simplifying the assembly process.
  - This length for TESLA-TYPE-III = 345.45mm  $\rightarrow$  283mm for ILC ( $\Delta = -62.45$  mm)
  - Since the length of the cavity is 1034.55 mm, this reduction in length leads to about 5 % increase in the accelerating field.



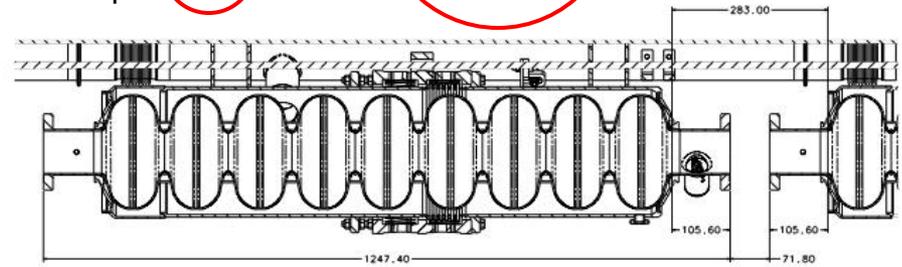
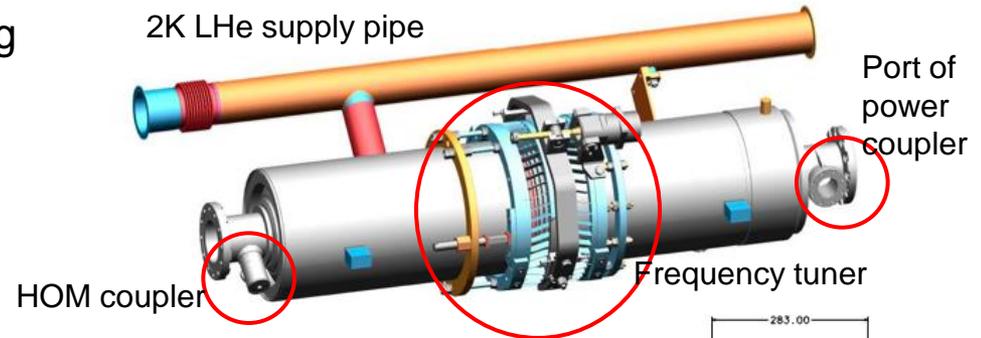
# Improvement of cryomodule for ILC

- Modifying the thermal radiation system from two shield system of 5K and 70K to one shield system of 40 K.
  - Improving the assembly process.
  - Changing the cooling scheme of the thermal shields and the thermal intercepts,

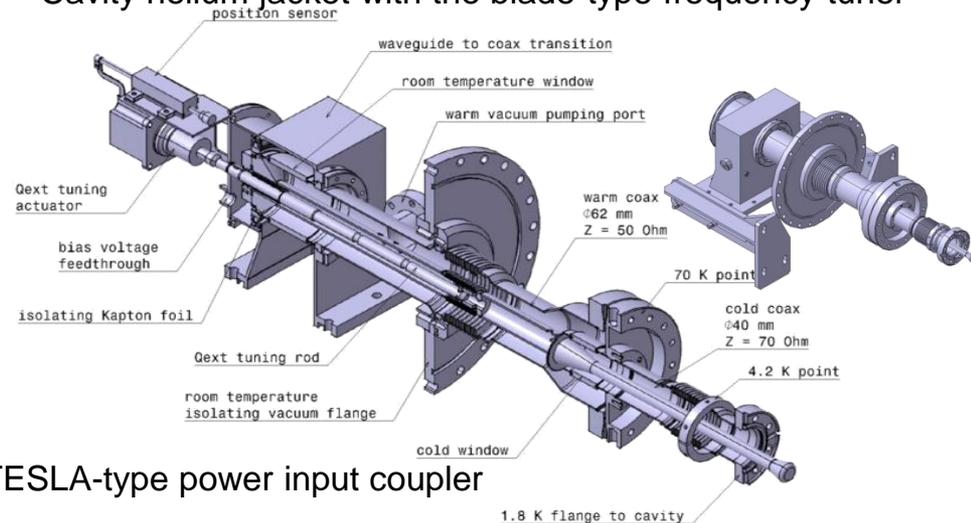


# Superconducting Cavity Helium Jacket

- Operating temperature of Superconducting cavity: 2K
  - Cavity material: Niobium
  - Saturated vapor pressure liquid helium cooling( T=2K, P=3.1kPa)
- Helium vessel (Cavity jacket)
  - Material: Titanium
  - The ratio of thermal contraction is almost same as Niobium
    - Ti :0.134%, Nb:0.129%
  - Length of helium jacket: 1036.2mm
    - Thermal contraction by cooling = 0.05 mm
- Components for helium jacket
  - Frequency tuner
    - Mechanical motor at 5K:slow tuning of cavity frequency
    - Piezo: fast tuning(1200Hz)
  - Input coupler
  - HOM coupler
  - 2K LHe supply pipe
    - Material: Titanium or Stainless steel
  - Slide support structure



Cavity helium jacket with the blade-type frequency tuner



TESLA-type power input coupler

# 2K saturated liquid helium supply pipe-1

## Supplying 2K liquid helium

- The total length of 154m along the one cryo-unit: straight pipe of ID= 72mm + Helium vessel to 2-phase pipe cross-connect of ID=55mm (length= $\sim$ 200mm)
- Heat load at cavity is removed by evaporation of liquid helium.
- In case that the area of evaporation is not sufficient, stable cooling is not kept.
  - The 2K supply pipe is filled with liquid helium.



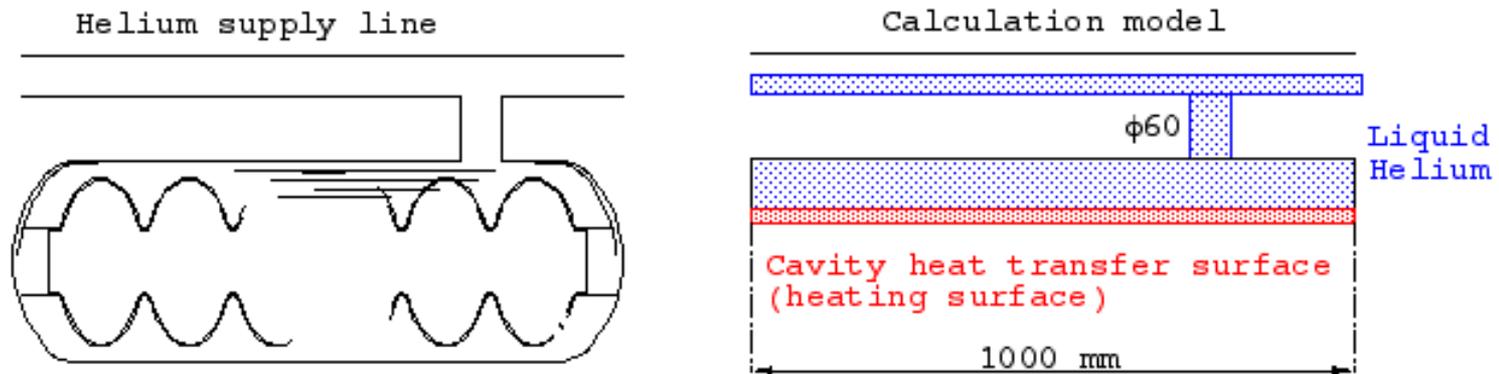
Cavity vessel and 2K helium supply pipe

# 2K saturated liquid helium supply pipe-2

Calculation of the temperature profile in the liquid helium with heat load.

- Heat load: 30W for four cavities
- Heating surface is the cavity surface, and the shape of 9 cells is assumed to be cylinder for simplification.
  - Pipe diameter between LHe supply line and cavity jacket = 60 mm
  - Cavity jacket length = 1000 mm
  - Distance between cavity heating surface and jacket inner surface = 6 mm
- Thermal calculation is performed with the two fluid model of super-fluid component and normal-fluid component (with viscosity and entropy).

## Calculation model

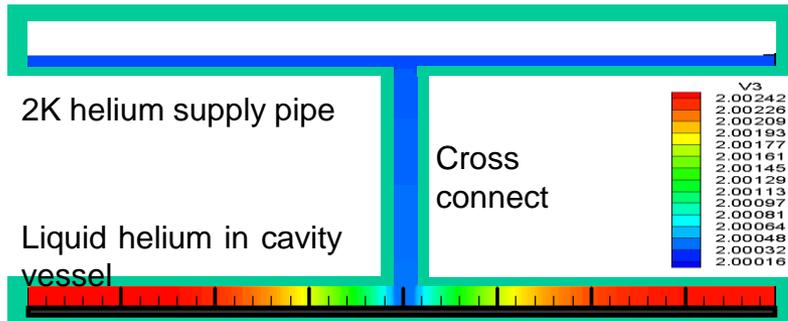


Cavity vessel and 2K helium supply pipe

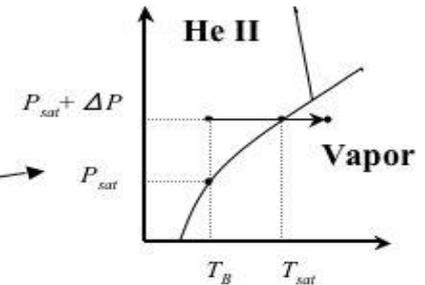
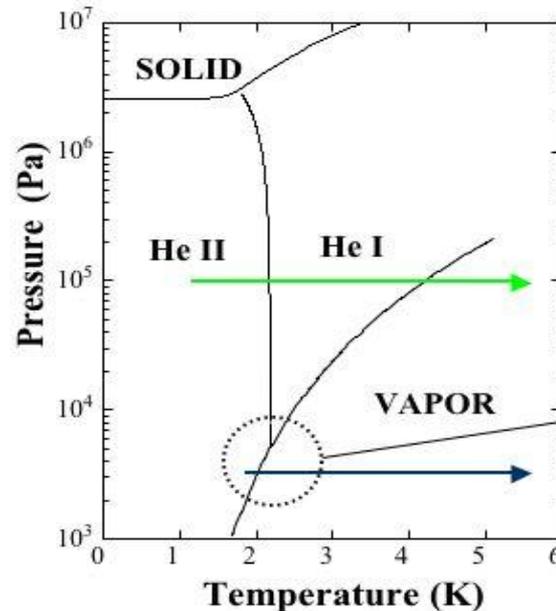
# 2K saturated liquid helium supply pipe-3

## Calculation results

- There exists temperature profile which shows the turbulent condition in the superfluid helium.
  - At the both ends,  $T = 2.0024$  K, and at the liquid surface,  $T = 2.000$  K.
- The temperature gradient is induced in the sub-cooled condition by the hydraulic head pressure from the liquid surface to the heating area.
- Smaller the evaporation area leads to higher temperature of the bulk helium, and to smaller sub-cooled condition.
  - Easy to happen a vapor film on the heating surface and decrease of cooling efficiency.

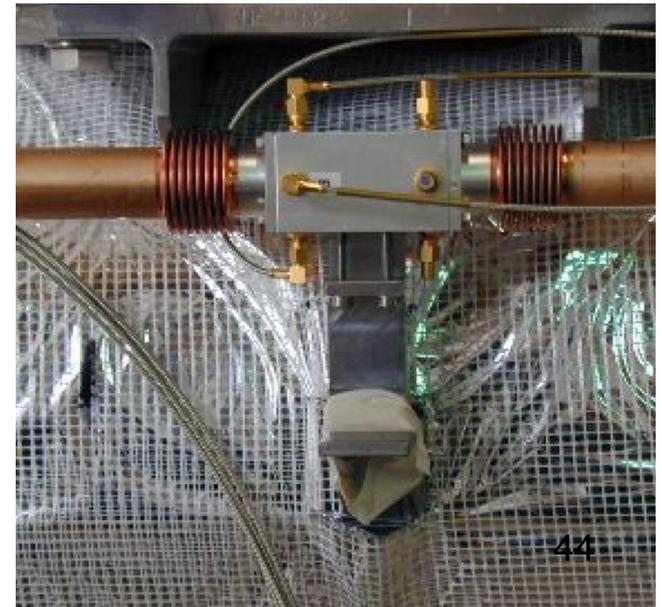


P-T diagram of He



# Position change of cavities during cool-down/warm-up -1

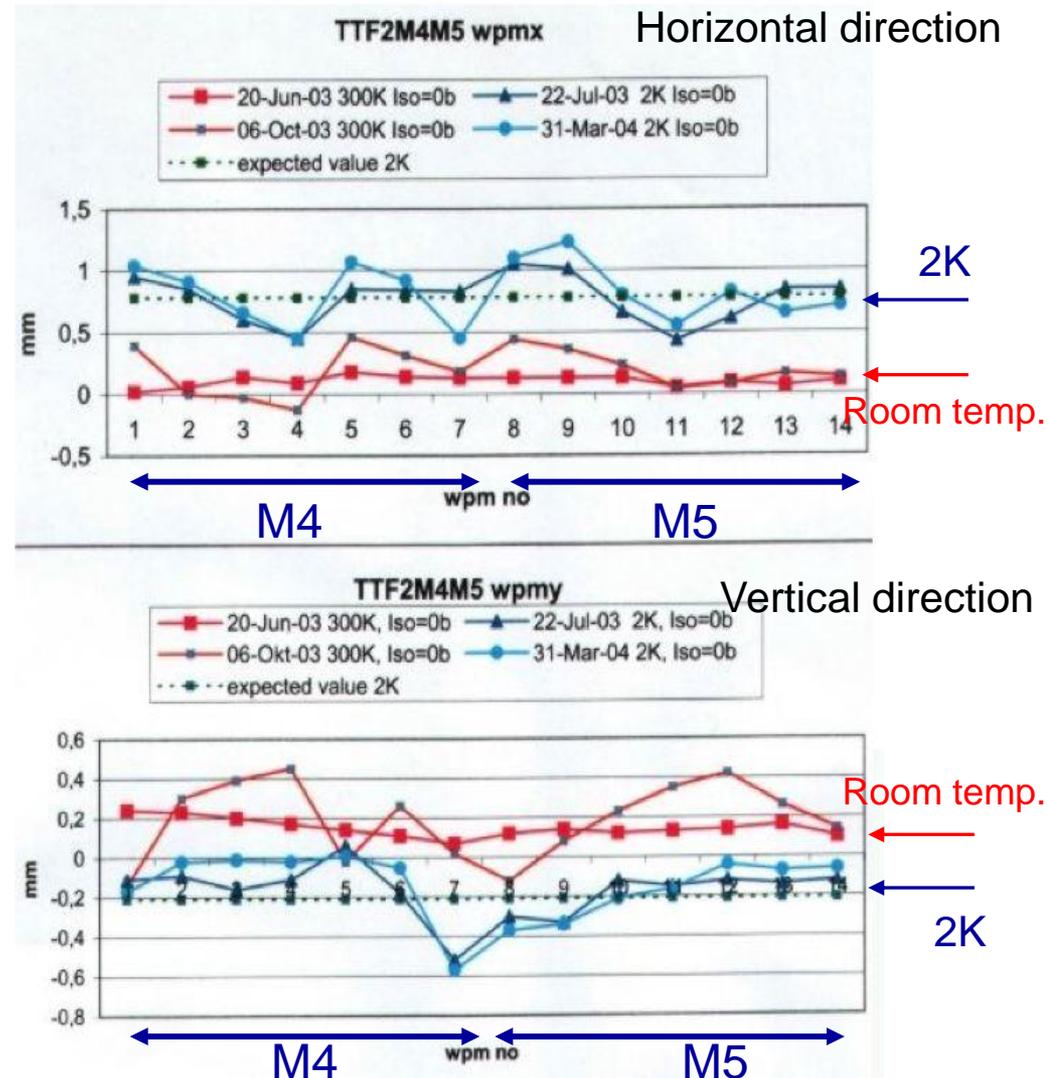
- Alignment of cavities is performed in room temperature.
  - Alignment tolerance for ILC:
    - Cavity : XY directions =  $\pm 0.3\text{mm}$
    - Quadrupole : XY directions =  $\pm 0.3\text{mm}$
- Positions of cavities and quadrupoles are changed by thermal contraction during cool-down and warm-up
  - Requirement of study for position change and the reproducibility by cool-down and warm-up
    - Measuring sensor : Wire Position Monitor (WPM)
    - WPM consists of 4 electrical terminals which locate 90 degrees in azimuthal direction.
    - Beryllium copper wire of  $\phi 0.5\text{ mm}$  is stretched in WPMs.
      - Tension =  $100\text{kg/mm}^2$ , sagging of wire =  $2.07\text{mm}$
    - The wire is supported from the components at room temperature, and then the wire position is not influenced by cool-down.



# Position change of cavities during cooldown/warmup -2

- Cavity position change while thermal cycles
  - WPM#1~7:Module-4
  - WPM#8~14:Module-5
  - Module-4 and 5 were connected with a bellow pipe.
- In the horizontal direction
  - Alignment error in room temp. < 0.1mm
  - Position change at 2K from the base line
    - 1<sup>st</sup> cooldown:  $-0.3\text{mm} < \Delta < +0.3\text{mm}$
    - 2<sup>nd</sup> cooldown:  $-0.3\text{mm} < \Delta < +0.5\text{mm}$
  - After warmup:  $-0.1\text{mm} < \Delta < +0.5\text{mm}$
- In the vertical direction
  - Alignment error in room temp. < 0.21mm
  - Position change at 2K from the base line
    - 1<sup>st</sup> cooldown :  $-0.35\text{mm} < \Delta < +0.25\text{mm}$
    - 2<sup>nd</sup> cooldown :  $-0.4\text{mm} < \Delta < +0.2\text{mm}$
  - After warmup :  $-0.2\text{mm} < \Delta < +0.5\text{mm}$

Not good in reproducibility of the cavity position at 2K.



# Measured heat load of cryomodules

- The heat loads of cryomodules measured in DESY are listed in the table.
- Heat load of 5 cryomodules:
  - Heat load at 2K < 3.5W
  - Heat load at 4.3K = 13~14.5W
- Heat load at RF operation (ILC specification):
  - Dynamic load at 2K = ~10 W
  - Dynamic load at 5K = ~4 W
  - Dynamic load at 40K = ~90 W

Status:15-Sep-04 R.Lange -MKS1-

Designed, estimated and measured static Cryo-Loads TTF-Modules in TTF-Linac										
Module	40/80 K [W]			4.3K [W]			2 K [W]			Notes
Name/Type	Design	Estim.	Meas.	Design	Estim.	Meas.	Design	Estim.	Meas.	
Capture			46,8			3,9			5,5	Special
Module 1 I	115.0	76.8	90.0 *	21.0	13,9	23.0 *	4,2	2,8	6,0 *	Open holes in isolation
Modul1 rep. I	115.0	76.8	81,5	21.0	13,9	15,9	4,2	2,8	5,0	2 end-caps
Module 2 II	115.0	76.8	77,9	21.0	13,9	13.0	4,2	2,8	4,0	2 end-caps
Module 3 II	115.0	76.8	72.0 **	21.0	13,9	48.0 **	4,2	2,8	5,0 *	Iso-vac 1E-04 mb, 2e-caps
Module 1* II	115.0	76.8	73.0	21.0	13,9	13.0	4,2	2,8	<3.5	1 end-cap
Module 4 III	115.0	76.8	74	21.0	13,9	13.5	4,2	2,8	<3.5	1 end-cap
Module 5 III	115.0	76.8	74	21.0	13,9	13.0	4,2	2,8	<3.5	1 end-cap
Module SS	115.0	~76.8	72.0	~21.0	~13.9	12.0	~4.2	>2,8	4,5	Special, 2 end-caps
Module 3* II	115.0	76.8	75	21.0	13,9	14	4,2	2,8	<3.5	1 end-cap
Module 2* II	115.0	76.8	74	21.0	13,9	14,5	4,2	2,8	<4,5	2 end-caps
Module 6 EP	Type III, EP-Cavities Goal:Solution close to XFEL Modules									(Assembly End-04??)
Design and estimated values by Tom Petersen 1995 -Fermilab-								Modules under Test in TTF2-Linac		

## Heat load at operation (rough calculation)

2K:10W and 4K:40W -> 80W at 4K

1 cooling unit (240 cryomodules) : 80 x 240=19200W

The planed refrigerator power : 25kW@4K, 30% operation margin

## Cryomodule configuration at DESY FLASH

