5 K Shield Study of STF Cryomodule (up-dated)

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KEK

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1. Original heat balance data and cooling scheme
2. Thermal calculations with the STF cryomodule
3. Cost study with or without 5 K shield
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Original heat loads scaled from TESLA TDR by Tom Peterson (in RDR)

Heat Load @ 2 K

	Static	Dynamic
RF load	NA	7.46
Supports	0.6	NA
Input Coupler	0.55	0.16
Current Leads	0.28	0.28
Others	0.27	1.76
Total	1.70	9.66

Total : 11.36 W

Heat Load @ 40 K

	Static	Dynamic
Radiation	32.5	NA
Supports	6.0	NA
Input Coupler	15.5	60.1
Others	5.2	28.2
Total	59.2	94.3

Total : 153.5 W

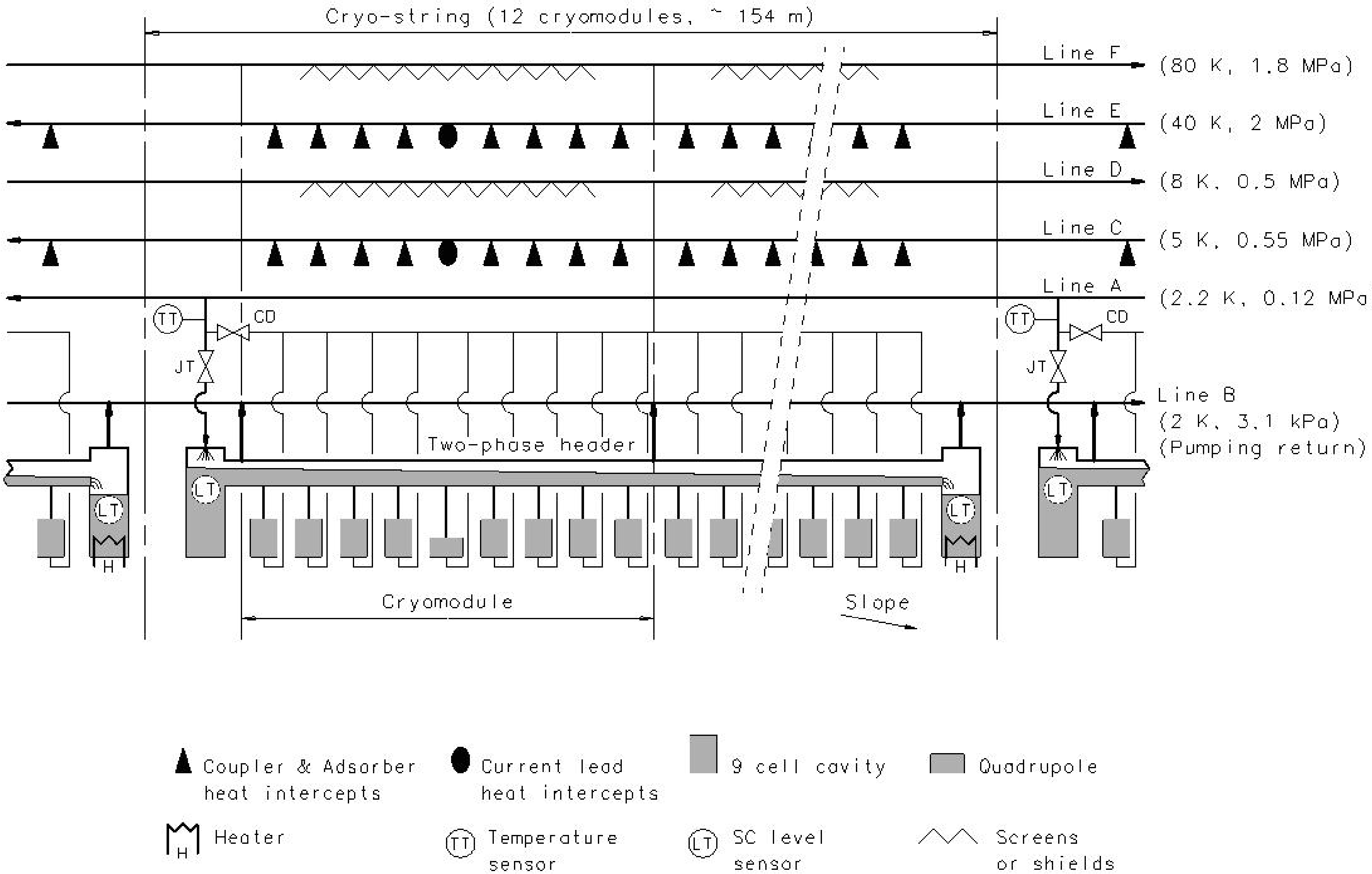
Heat Load @ 5 K

	Static	Dynamic
Radiation	1.41	NA
Supports	2.40	NA
Input Coupler	1.48	1.32
HOM Coupler (cable)	0.29	1.82
HOM Absorber	3.13	0.76
Current Leads	0.47	0.47
Diagnostic Cable	1.39	NA
Total	10.56	4.37

Total : 14.9 W

It is assumed that in the cryomodule without the 5 K shield, the heat load of 1.41 W at 5 K by radiation in the table goes into the 2 K region.

Cooling Scheme by T. P. (in RDR)



Thermal calculation of STF cryomodule model (Thermal Radiation-1)

- **Conditions of the calculation model (STF cryomodule)**
  - **80 K thermal shield**
    - The shield length: 5.732 m
    - The shield surface area: 14 m^2
    - Emissivity: 0.2 (as oxidized surface)
  - **2 K components**
    - Gas return pipe, 4 helium vessels, beam pipes, LHe supply pipe
    - Surface area of the components : 9.75 m^2
    - Effective emissivity : 0.03

CERN data

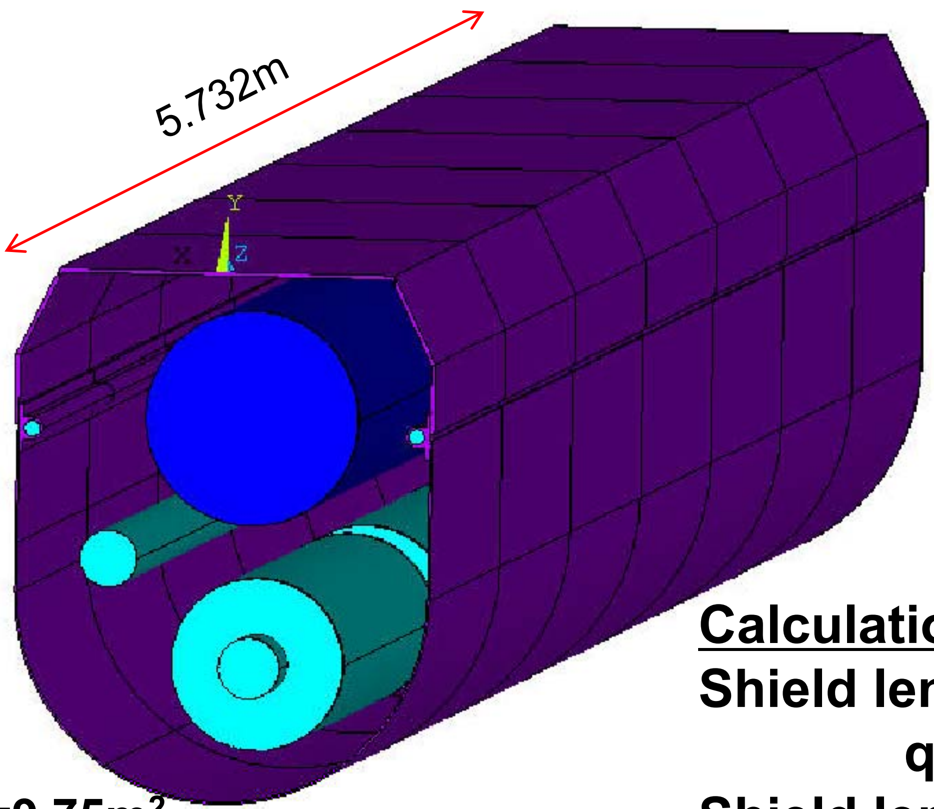
Heat flux by radiation from 80K -> 2K = 0.05 W/m^2

From the equation of heat flux between the parallel planes

$$q/A = \sigma (T_1^4 - T_2^4)/(1/\varepsilon_1 + 1/\varepsilon_2 - 1)$$

$q/A = 0.05 W/m^2$, $T_1 = 77K$, $T_2 = 4K$, $\varepsilon_1 = 0.2$ $\Rightarrow$ $\varepsilon_2 = 0.027$

Thermal calculation of STF cryomodule model (Thermal Radiation-2)



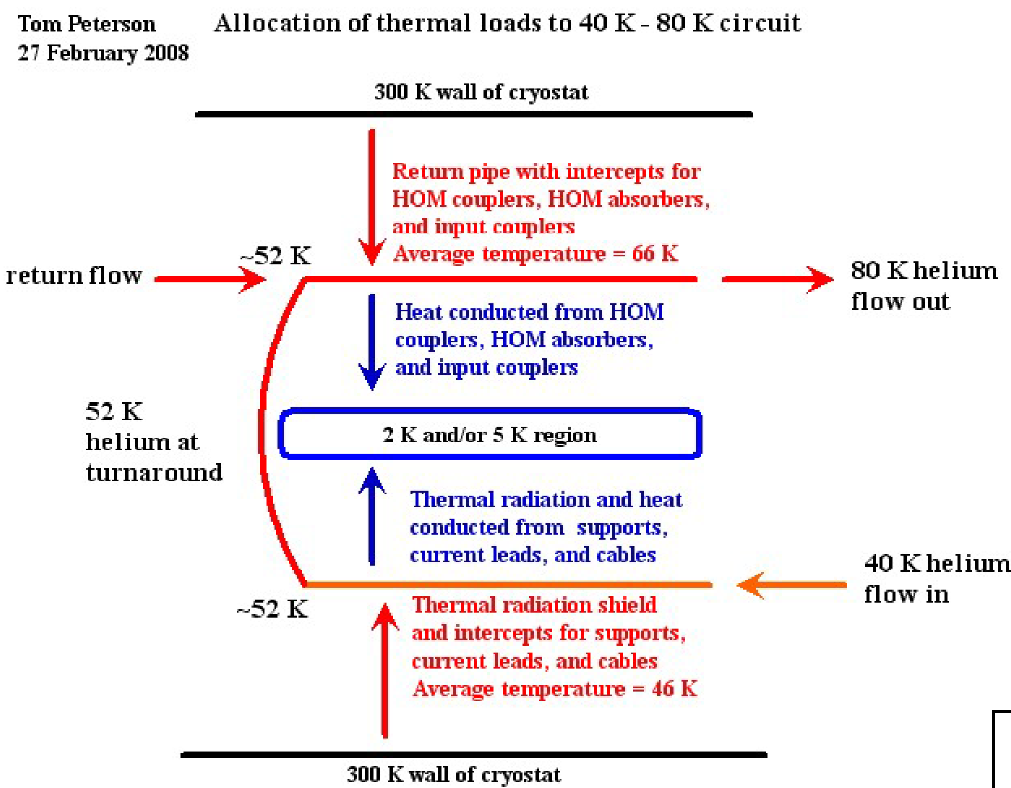
80 K shield surface=14m^2
Emissivity=0.2

2K surface=9.75m^2
Emissivity=0.03

<u>Calculation result;</u>
Shield length=5.732 m
q = 0.83 W at 2 K
Shield length for ILC = 12.653 m
q = 1.83 W at 2 K from 80 K

Thermal calculation by ANSYS
(The effect of the surface shape was checked.)

Cooling scheme of the 40K~80K level proposed by Tom Peterson (CASE-2, C2)



In the original thermal calculation (CASE-1, C1)

40K GHe at inlet

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Intercepts for HOM couplers, HOM absorbers, input couplers — 54K

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Thermal radiation shield, intercepts for supports, current leads and cables — 74K

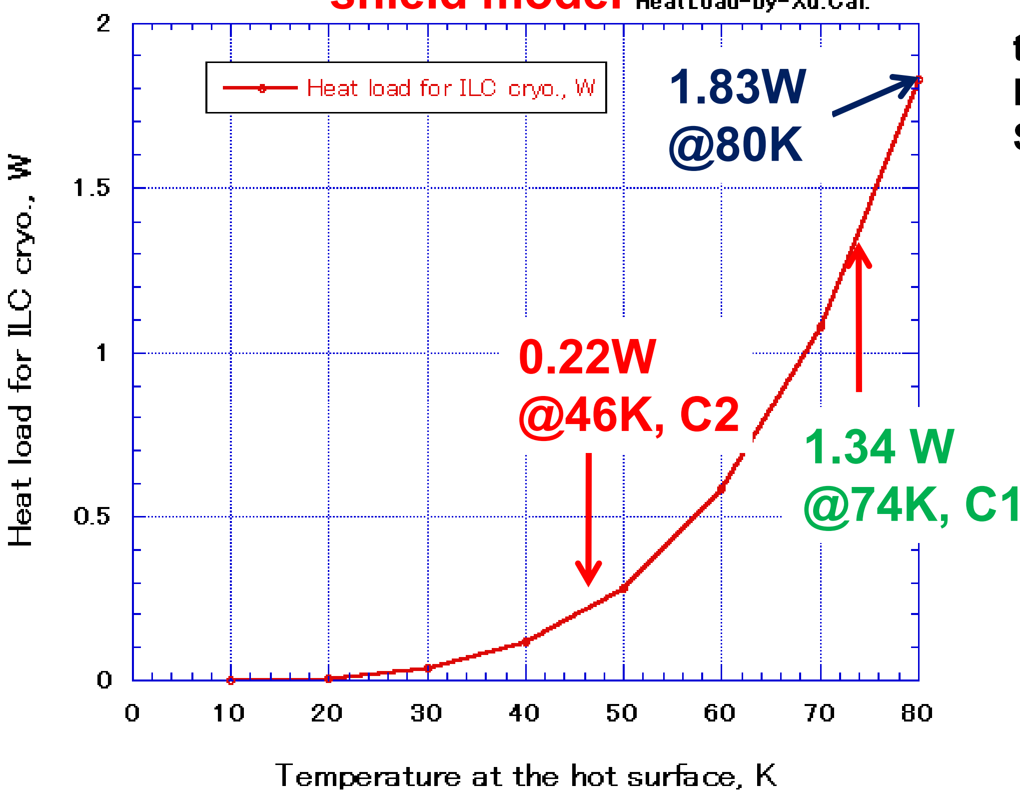
⇩

80K GHe at inlet

	In	Forward	Backward	Out
C 1	40K	54 K	74K	80K
C 2	40K	46K	66K	80K

Re-calculation of heat load with the temperature distribution by T.P. model (1)

Heat load by thermal radiation as a function of temperature without 5K shield model



This calculation includes the geometrical factor of GRP, cavity vessel and LHe supply pipe.

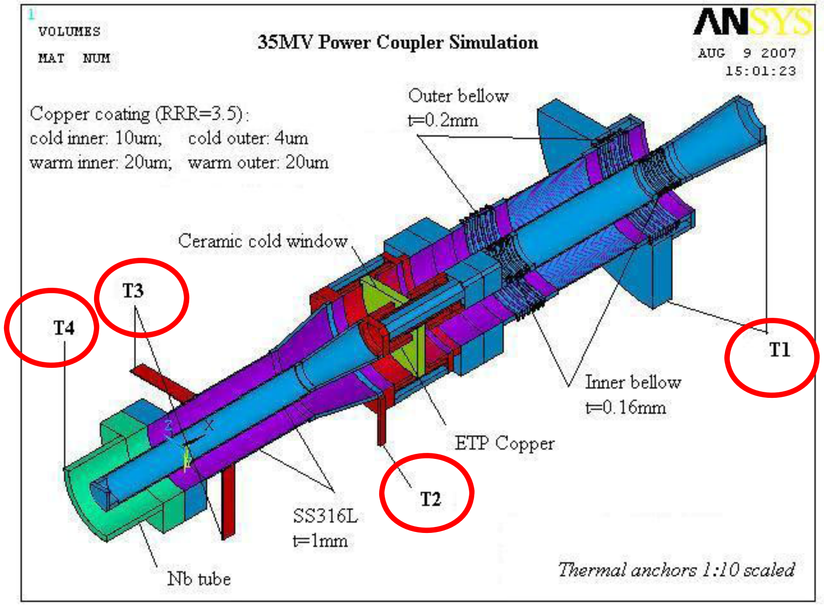
With 5 K shield model:

Two shields at 80 K and 5 K are assumed to be parallel and same surface area.
Heat flux=0.05 W/m^2 (from 80K to 5K)
Surface area=30.9 m^2

Estimated heat load at 5K shield

77K → 5K	1.55W	
74K→ 5K	1.32W	C1
46K→ 5K	0.20W	C2

Re-calculation of heat load with the temperature distribution by T.P. model (2)



Original thermal design of the input coupler;

T_1=300K, T_2 = 80 K, T_3=5K, T_4= 2K

Static Heat Load;

2.4W @80K, 1.0W@5K, 0.017W@2K

Dynamic Heat Load;

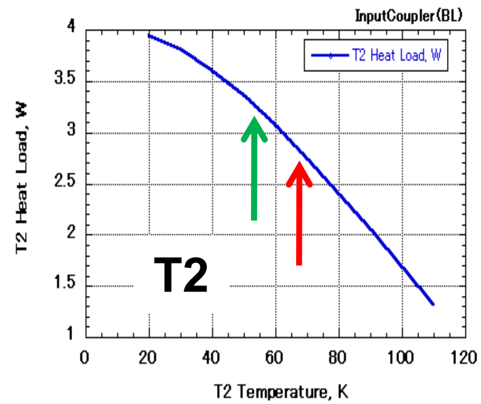
3.0W @80K, 0.2W@5K, 0.03W@2K

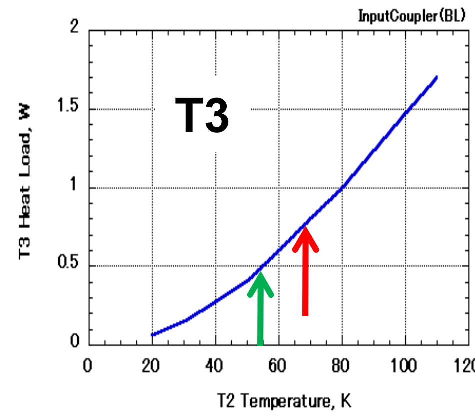
Total Loss @300K = 359W for one coupler

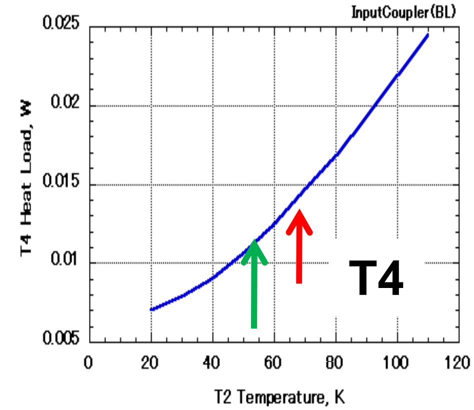
Total Loss @300K=3.12 kW for one module

Static heat load through STF-BL input coupler as a function of temperature

- **T_1 = 300K, T_3 = 5K, T_4 = 2K (Fixed)**
- **T_2 = parameter for calculation**







T_2=54K, C1

0.011 W @ 2K

0.487 W @ 5K

3.25 W @ 40 K

T_2=66 K, C2

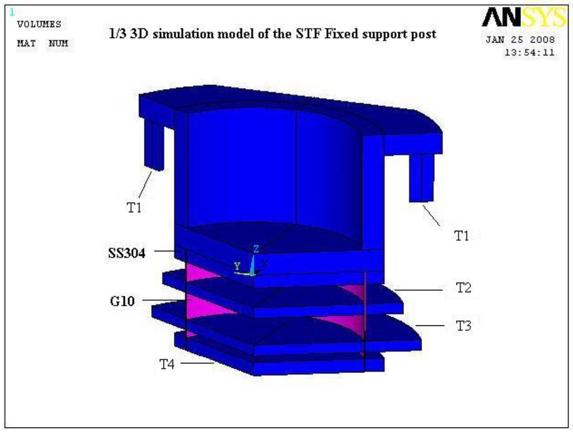
0.014W @ 2K

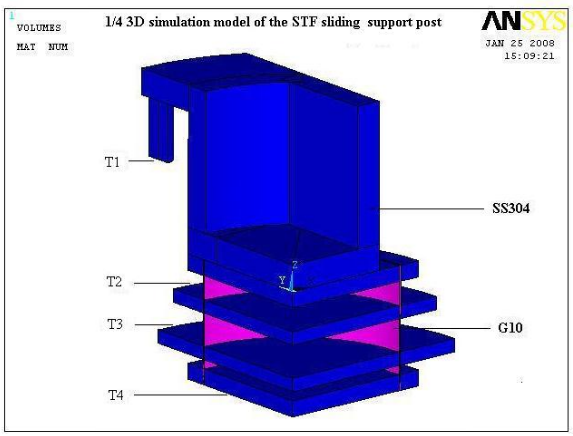
0.720W @ 5K

2.88W @ 40K

(for one coupler)

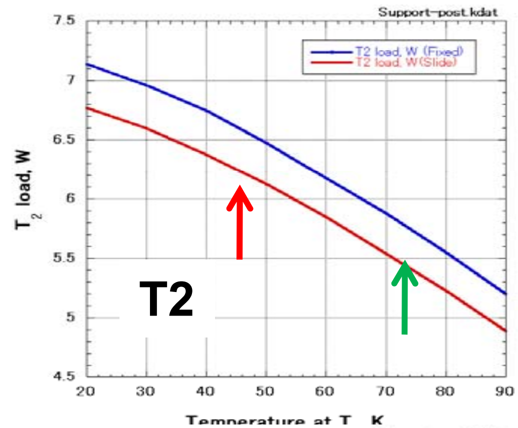
Re-calculation of heat load with the temperature distribution by T.P. model (4)

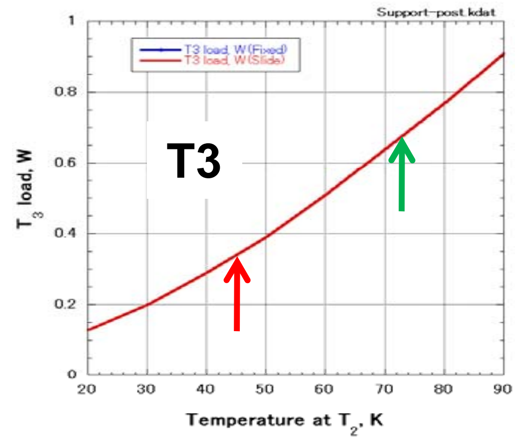


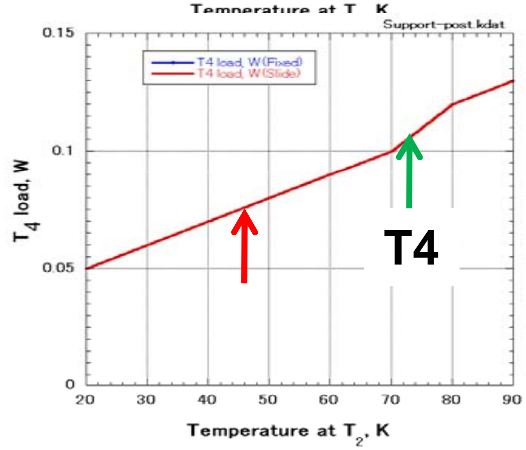


Static heat load through support posts as a function of temperature

- T_1 = 300K, T_3 = 5K, T_4 = 2K (Fixed)
- T_2 = parameter for calculation







T_2=74 K, C1

Fixed post

- 0.108W @ 2K
- 0.685W @ 5K
- 5.76W @ 40K

Slide post

- 0.108W @ 2K
- 0.685W @ 5K
- 5.43 W @ 40K

T_2=46 K, C2

Fixed post

- 0.075W @ 2K
- 0.353W @ 5K
- 6.58W @ 40K

Slide post

- 0.075W @ 2K
- 0.353W @ 5K
- 6.23W @ 40K

Heat loads of STF cryomodule for Case1

Heat Load @ 2 K

	Static (w./w.o. 5K shield)	Dynamic
RF load	NA	7.46
Radiation	0.00 / 1.34	NA
Supports	0.32	NA
Input Coupler	0.095	0.26
Current Leads	0.28	0.28
Others	0.27	1.76
Total	0.97 / 2.31	9.76

Heat Load @ 5 K

	Static (w./w.o. 5K shield)	Dynamic
Radiation	1.32 / 0.00	NA
Supports	2.06	NA
Input Coupler	4.27	1.73
HOM Coupler (cable)	0.29	1.82
HOM Absorber	3.13	0.76
Current Leads	0.47	0.47
Diagnostic Cable	1.39	NA
Total	12.93 / 11.61	4.78

Heat Load @ 40 K

	Static (w./w.o. 5K shield)	Dynamic
Radiation	32.5	NA
Supports	16.62	NA
Input Coupler	28.18	26.01
Others	5.2	28.2
Total	82.5	54.2

Heat load for Case 1

	With 5K shield	Without 5K shield	Original
2K	10.73	12.07	11.36
5K	17.71	16.39	14.9
40K	136.7	136.7	153.5

Heat loads of STF cryomodule for Case2

Heat Load @ 2 K

	Static (w./w.o. 5K shield)	Dynamic
RF load	NA	7.46
Radiation	0.00 / 0.22	NA
Supports	0.23	NA
Input Coupler	0.12	0.26
Current Leads	0.28	0.28
Others	0.27	1.76
Total	0.90 / 1.12	9.76

Heat Load @ 5 K

	Static (w./w.o. 5K shield)	Dynamic
Radiation	0.20 / 0.00	NA
Supports	1.06	NA
Input Coupler	6.24	1.73
HOM Coupler (cable)	0.29	1.82
HOM Absorber	3.13	0.76
Current Leads	0.47	0.47
Diagnostic Cable	1.39	NA
Total	12.78 / 12.58	4.78

Heat Load @ 40 K

	Static (w./w.o. 5K shield)	Dynamic
Radiation	32.5	NA
Supports	19.04	NA
Input Coupler	24.97	26.01
Others	5.2	28.2
Total	81.7	54.2

Heat load for Case 2

	With 5K shield	Without 5K shield	Original
2K	10.66	10.88	11.36
5K	17.56	17.36	14.9
40K	135.9	135.9	153.5

Operation cost (10 years= 66000H)

Efficiency in Watts/Watt (by T. P. in RDR)

T_c	2 K	5 K ~ 8 K	40 K ~ 80 K
$W_{@300K}/W_{@Tc}$	702.98	197.94	16.45

Original T.P. data
Heat load of 1.41 W@2K =0.991 kW at 300K,
Total heat loads at three temp. levels = 13.46 kW at 300 K

Required power at 300 K per cryomodule

	T. P. model (Original)	STF, C1	STF, C2
With 5 K shield, kW	**13.46**	**13.30**	**13.21**
Without 5 K shield, kW	**14.17**	**13.98**	**13.32**
Difference between with and w/o 5 K shield, kW	**0.71**	**0.68**	**0.11**

Required extra operation cost for 10 years, **k$**

	$/kWh @2006	T.P. model	STF C1	STF C2
Japan	0.117	**5.48**	**5.25**	**0.85**
USA	0.063	**2.95**	**2.83**	**0.46**
Germany	0.077	**3.61**	**3.46**	**0.56**

Cost study of cryogenic system from T.P. study-1

(Heat load of 1.41W at 5K by radiation is added to the 2K region.)

Cryogenic system cost

- Cost impact is calculated for cryoplants and their installation but not for distribution system
  - Installed plant power increases from 4.28 to 4.49 MW for each of the large cryoplants
  - Assume capital cost increases by installed power ^0.6
  - $7.59 M total cryogenic plants capital cost increase
  - 1815 standard 1.3 GHz cryomodules including sources (not including multi-magnet cryomodules)
- Cryosystem additional M&S is $4200 per cryomodule
- Cryogenic plant operating power
  - Increases from 3.34 MW to 3.50 MW for each of the 10 large plants
  - Total of 1.6 MW added for ILC cryogenic system

(0.882 kW per cryomodule)

- Added operating cost at $0.10/kW-hr is $1.38M/yr or $770 per cryomodule per year

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Cost study of cryogenic system from T.P. study-2

	Original model by T.P.	C1 model	C2 model
Heat Load at 5K by Radiation	1.41 W	1.32 W	0.20 W
Converted Heat Load Diff. at 300 K per Module	0.71 kW	0.68 kW	0.11 kW
Cryo. Additional M&S Cost	4.2 K$	4.02 k$	0.65 k$
Additional Operation Cost (10 years)	7.7 k$	6.7 k$	1.09 k$
Total Cost	11.9 k$	10.7 k$	1.74 k$

Calculation for STF-C1 model,

For cryogenic additional M&S cost

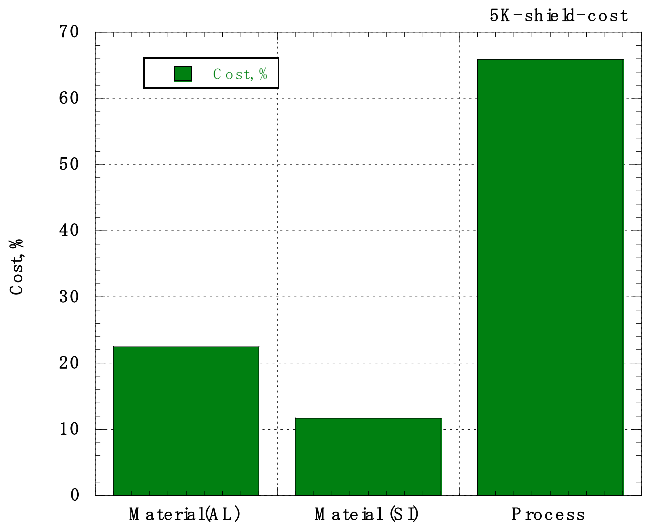
4.2k$ × (0.68/0.71) =0.67 k$

For additional 10 year operation cost of cryo-plant

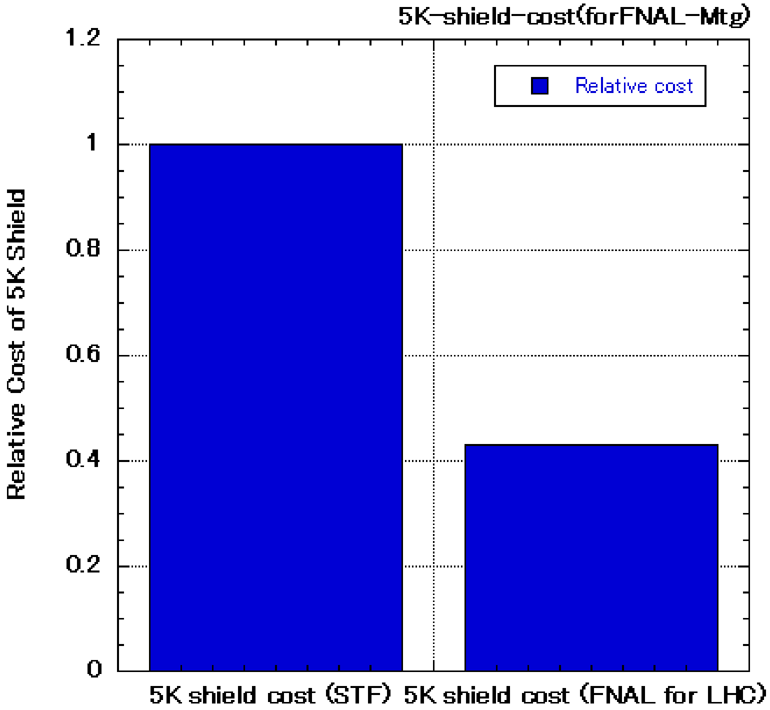
0.882 × 66000 × 0.117 × (0.68/0.71) = 10.7 k$ in Japan.

5 K shield cost of STF cryomodule

- **The cost estimation of 5 K shield is based on the RDR study by the Japanese company.**
- **For the cost estimation of 5 K shield of the STF cryomodule, the learning ratio of the man-hours of processing and discount of the material cost for 2100 cryomodules (for 8 cavities) are considered.**
- **The estimated cost of 5 K shield does not include the company profit.**

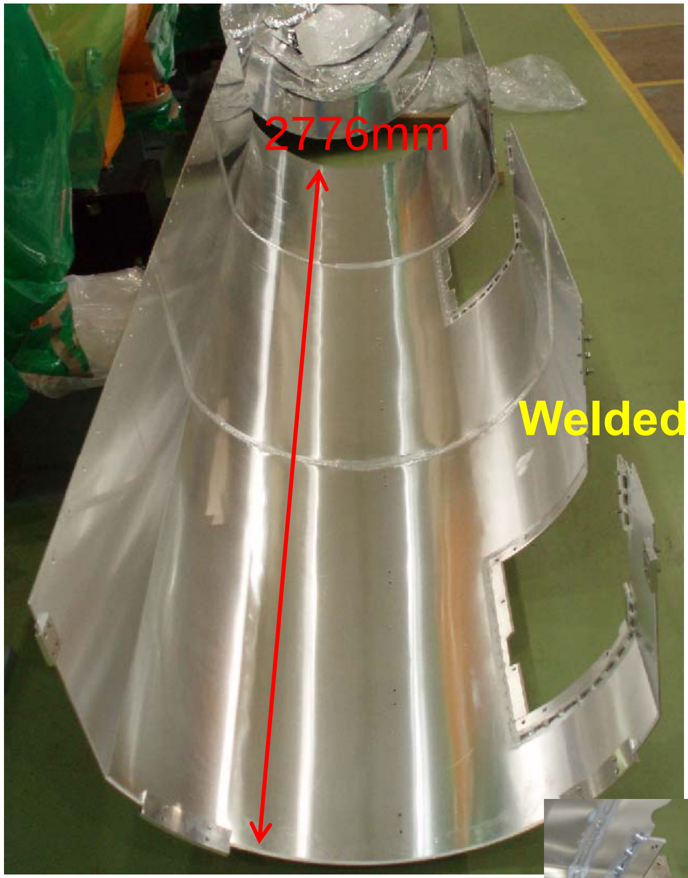


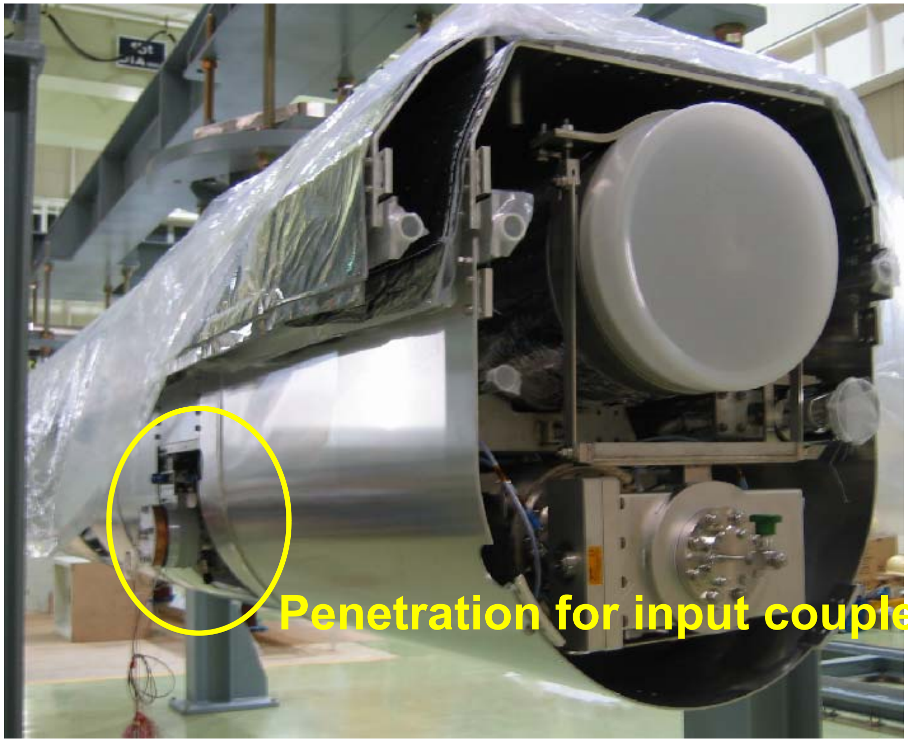
Cost for material and process of the STF 5 K shield
(The material cost includes Al plate and 10 layers SI.)

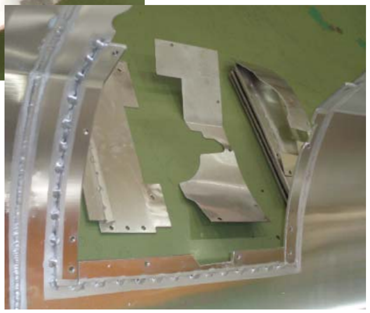


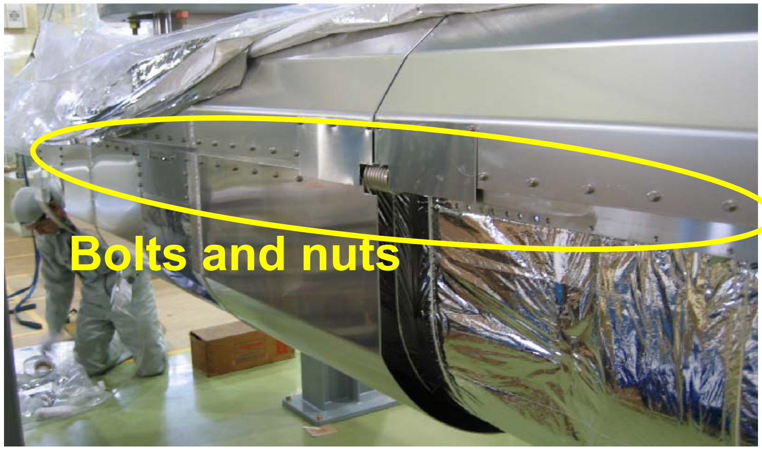
Comparison between the 5 K shield costs between STF and FNAL
(The 5 K shield cost by FNAL and LHC are estimated for the magnet cryostat. This shield does not have penetrations for the input couplers.)

STF-cryomodule thermal shield





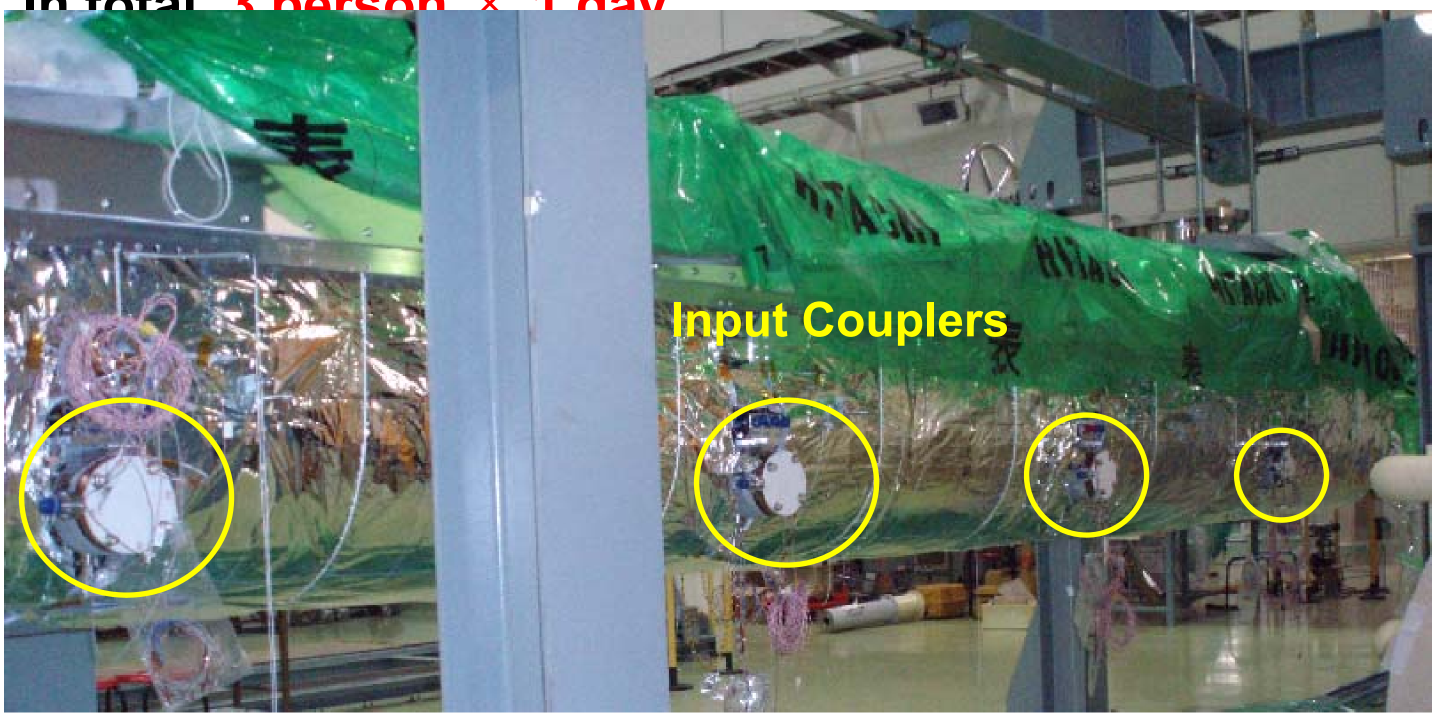




1. The length of one piece is 2776 mm.
2. The three plates are welded for this one piece.
3. Connections between upper-side, lower side and cooling pipes are done by bolts and nuts.

Assembly cost of the shield and SI

- **Assembling and welding the upper and down shields**
  - **Assembling shields: two persons × 0.5 day**
- **Assembling SI on the 5 K shield and around the input couplers**
  - **4 persons × 0.5 day**
- **In total 3 person × 1 day**



Super Insulations on the 5 K shield

Comparison of the costs including all items for the 5K shield of STF cryomodule

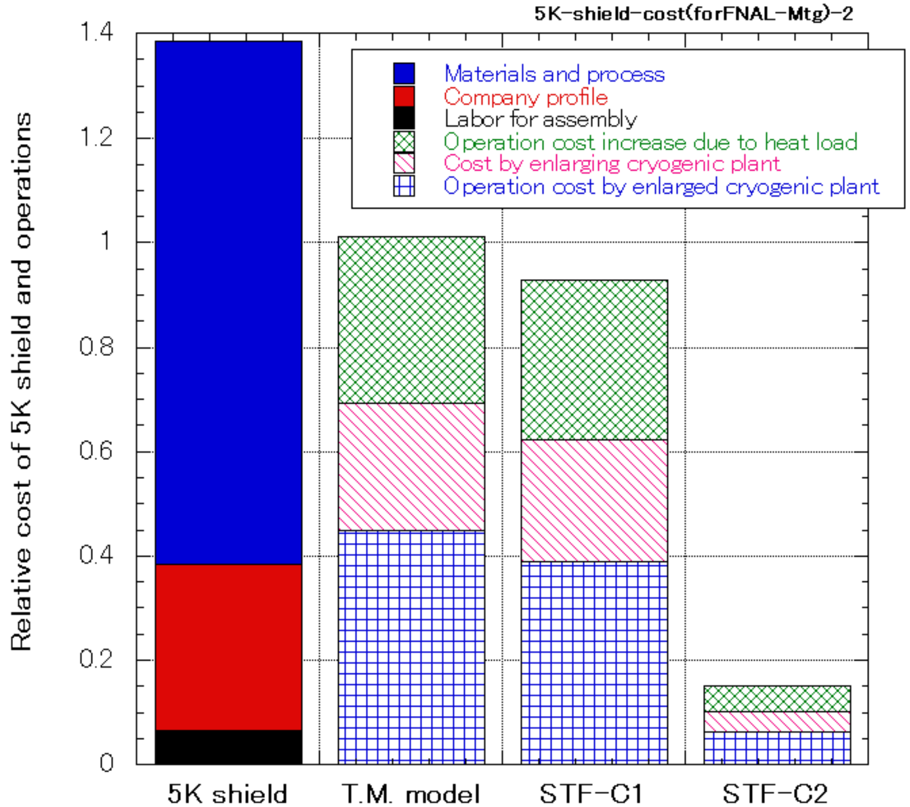
In case of removing 5 K shield;

Cost increase items

1.Operation cost by increasing heat load of cryomodule
2.Enlarging the cryogenic plant by increasing the heat load
3.Operation cost by the enlarged cryogenic plant

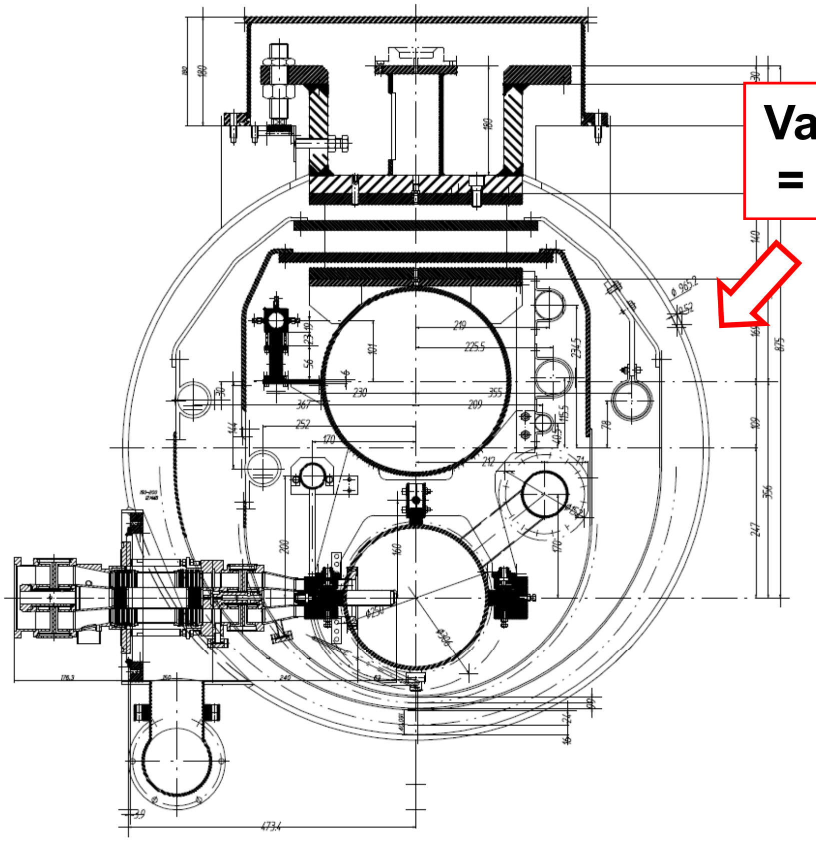
Cost reduction items

1.5 K shield components
2.Labor cost for assembly
3.Company profit for 5 K shield and assembly

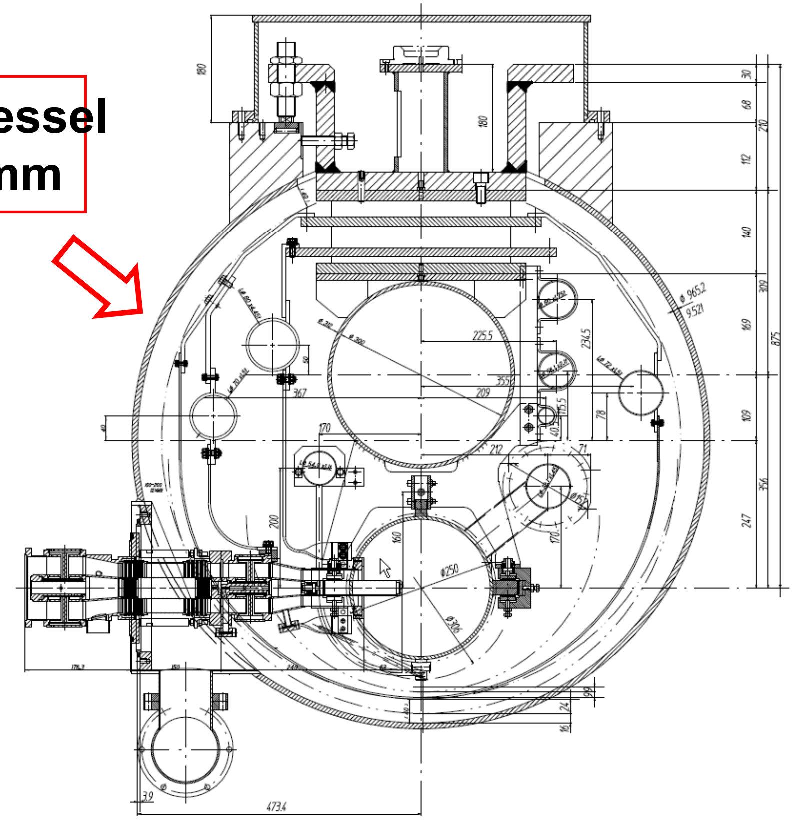


With the model of STF cryomodule, the additional cost by removing the 5K shield (operation and enlarging cryogenics system) is ~ 10 % of the 5K shield cost (component and assembly).

Study of the cryomodule cross-section (1)



Vacuum vessel
= ϕ 965.2mm



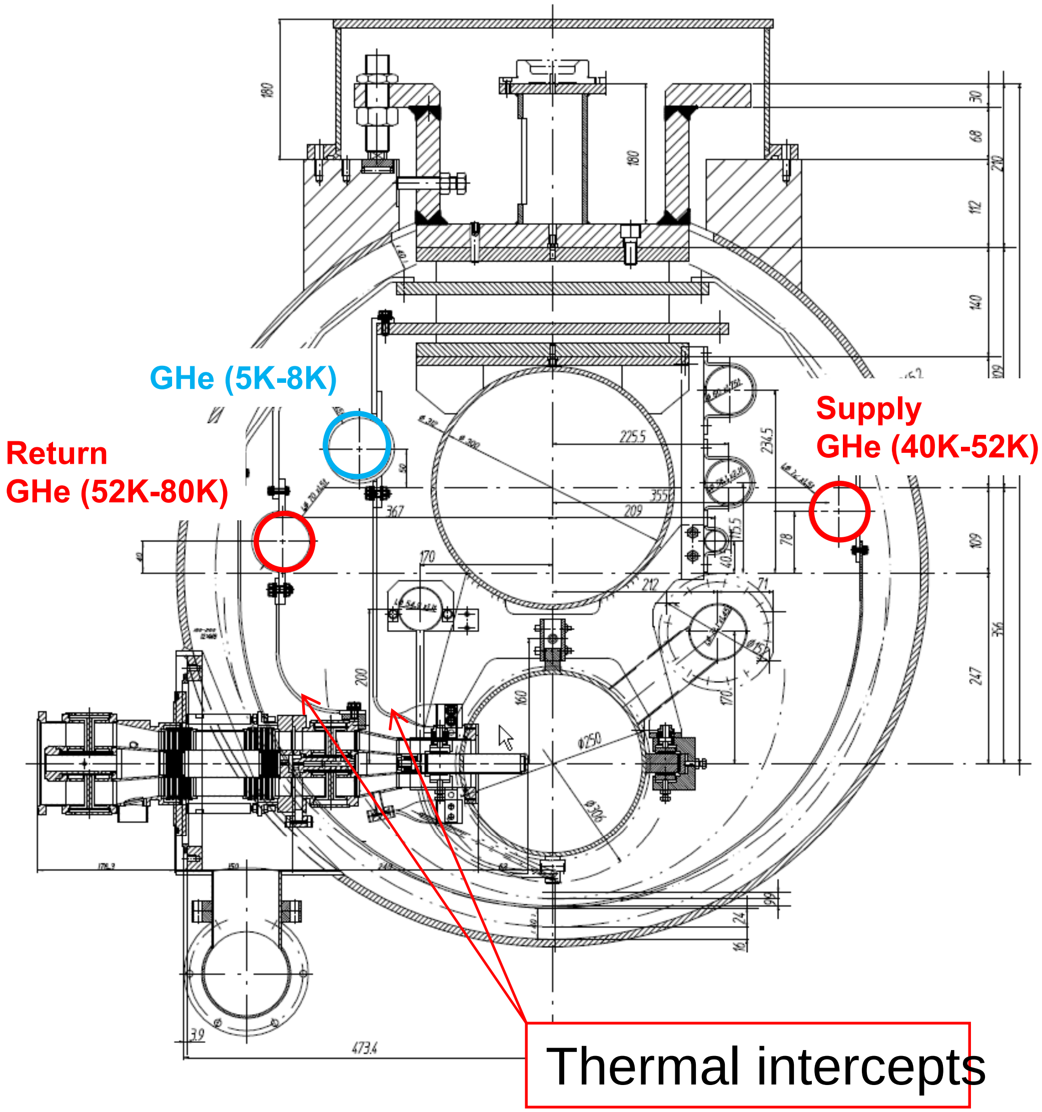
Two shields model based on TTF-III with KEK input coupler

1. **40K-80 K shield with 30-layer-SI**
2. **5K-8K shield with 10-layer-SI**
3. **5-layer-SI around cavity jacket, GRP and LHe supply pipe**

One shield model

1. **40K-80 K shield with 30-layer-SI**
2. **5-layer-SI around cavity jacket, GRP and LHe supply pipe**
3. **5K cooling pipe support**

Study of the cryomodule cross-section (2)



- **Thermal interceptors**
  - **Requirement of the design modification in the thermal interceptors**
  - **The interceptors for input couplers and the RF cables are directly connected to the terminals which are fabricated on the return cooling pipe.**
- **By this modification, assembly of the thermal shields and the interceptors will be simple.**
  - **Reduction in labor cost**

Summary and proposal

1. **The sum of increments of the operation cost and the reinforcement cost of the cryogenic plant is about 10 % of the sum of components and assembly labor costs of the 5K shield under the cooling scheme proposed by Tom Peterson.**
   - Increased heat load at 2 K by thermal radiation : 0.22 W
   - Assumption of the heat intensity by radiation : 0.05 W/m^2 (CERN data)
     - Assumed emissivity = 0.2 at 46 K (oxidized surface), 0.03 at 2 K (10-layer-SI)
2. **From calculation, removing the 5 K shield is effective on the cost reduction of the cryomodule.**
3. **The cooling scheme of the 80K shield should be changed as;**
   - 40K ~ 52 K (supply): Thermal radiation shield, intercepts for supports, current leads and cables
   - 52K ~ 80K (return) : Intercepts for HOM couplers, HOM couplers and input couplers
4. **Proposal of cryomodule design without 5K shield;**
   - Diameter of the vacuum vessel is not changed in case of the module design without 5 K shield.
   - 5K cooling pipe is necessary for thermal intercepts of input coupler, HOM coupler, HOM absorber, support posts and RF cables.
   - The location of cooling pipe should be modified for getting good thermal conditions of interceptors and assembly of the cold mass.
   - For STF-2 cryomodule, KEK will consider the module design and the cryogenic system without 5K shield .

Re-calculation of heat load with the temperature distribution by T.P. model (3)

Dynamic heat load of the input coupler;

T_1=300K, T_2 = 80 K, T_3=5K, T_4= 2K

Dynamic Heat Load;

3.0W @80K, 0.2W@5K, 0.03W@2K

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Dynamic heat load is proportional to integral resistivity along the input coupler;

T_1=300K, T_2 = 66 K, T_3=5K, T_4= 2K

3.0W @40K, 0.2W@5K, 0.03W@2K