Cryogenics and Cryomodule Design issues for SPL

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Outline:

- Heat Loads
- Cooling capacities
- Cryogenic schemes
- Cryomodule design issues
- Summary

Acknowledgements:

- F.Gerigk, C.Maglioni for contributions and help

Heat Loads and cryo-plant for SPL, 3.5 GeV ("Yellow-Book")

Assumptions:

- Dynamic load from quads neglected
- HOM and coupler loads at 2 K:
  - 40% and 3% of RF field loads
- Dynamic loads at 5-8 K and 50-75 K:
  - 40% and 115% of the static loads at 5-8 K and 50-75 K

Table 4.25: Nominal and ultimate SC cavity parameters for the dimensioning of the cryogenic system

Section	β	E_{acc} [MV/m] nominal/ultimate	Q_0 [10^{10}] nominal/ultimate	R/Q [Ω]	Active cavity length [m]	Cav. per cryo module	No. of cryo modules	String length [m]
1	0.65	19/20.9	1/0.5	290	0.692	6	7	85.8
2	1	25/27.5	1/0.5	570	1.064	8	9	135.6
3	1	25/27.5	1/0.5	570	1.064	8	8	120.5

Table 4.26: Estimated heat loads in watts per module assuming a 6% duty cycle

Temperature	2 K		5–8 K		50–75 K	
Cavity β	0.65	1.0	0.65	1.0	0.65	1.0
Static loss	3.5	4.4	15.2	18.9	88.7	110.4
Beam loss	11.45	14.26	–	–	–	–
RF nom.	21.5	59.6				
HOM nom.	8.6	23.8	6.1		102	
Coupler nom.	0.64	1.79				
Total dynamic nominal	42.2	99.5	6.1		102	
RF ult.	51.9	144.2				
HOM ult.	20.8	57.7	6.1		102	
Coupler ult.	1.56	4.33				
Total dynamic ultimate	85.7	220.5	6.1		102	

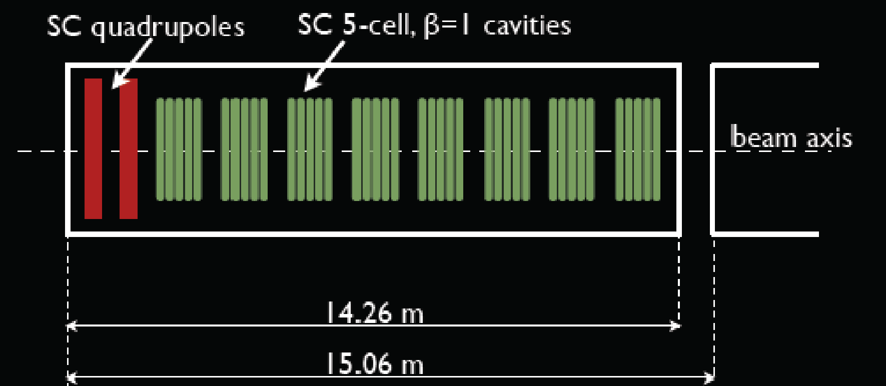
Table 4.27: Total heat load and installed capacities for a 6% cryo duty cycle

Temperature	2 K	5–8 K	50–75 K
Static [W]	99	427	2497
Dynamic nominal [W]	1986	146	2446
Dynamic ultimate [W]	4348	146	2446
Installed capacity [W]	4496	1180	9290
Equivalent at 4.5 K [kW]		15.8	

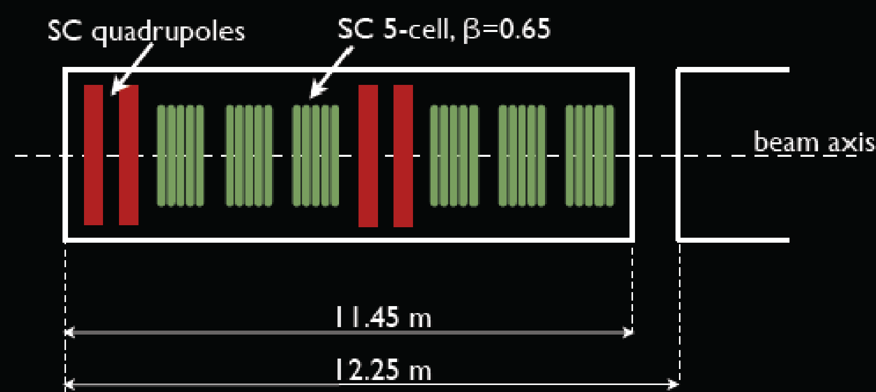
Updated baseline, HP-SPL (5 GeV)

Base-line cryo-modules

high-beta section:
- 704.4 MHz, 25 MV/m,
- 668 - 5094 MeV,
- 25 periods, 200 cavities,
- 377 m



low-beta section:
- 704.4 MHz, 19 MV/m,
- 180 - 668 MeV,
- 14 periods, 42 cavities,
- 86 m



in total: 463 m, 242 cavities, 2 families, 704 MHz

“RF frequency options for the SPL”, 9 November 2007, F. Gerigk

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Courtesy of F.Gerigk

Heat Loads for SPL: updated values

- LP-SPL (4 GeV), 2K:
  - β=1: 20 modules, 160 cavities, 301 m
  - β=0.65: 7 modules, 42 cavities, 86 m
  - 12.25 m length for β=0.65, 15.062 m length for β=1
  - Nominal/Ultimate: 4/12 MW beam power

HL [W] @ 2K per cryomodule

		β=0.65	β=1
	Cryo duty cycle	0.4%	0.4%
1	Static	3.50	4.40
2	Beam loss	11.50	14.30
3	Dynamic nominal	2.00	5.70
2+3	Total dynamic nominal (with beam loss)	13.50	20.00
4	Total dynamic ultimate (with beam loss)	16.50	28.00
1+2+3	Grand Total nominal	17.00	24.40
1+4	Grand Total ultimate	20.00	32.40

HL [W/m] @ 2K per unit length

	β=0.65	β=1
HL/m nominal [W/m]	1.39	1.62
HL/m ultimate [W/m]	1.63	2.15

- HP-SPL (5 GeV), 2K:
  - β=1: 25 modules, 200 cavities, 377 m
  - β=0.65: 7 modules, 42 cavities, 86 m
  - 12.25 m length for β=0.65, 15.062 m length for β=1
  - Nominal/Ultimate: 4/12 MW beam power

HL [W] @ 2K per cryomodule

		β=0.65		β=1	
	Cryo duty cycle	4%	8%	4%	8%
1	Static	3.50	3.50	4.40	4.40
2	Beam loss	11.50	11.50	14.30	14.30
3	Dynamic nominal	20.50	41.00	56.80	113.60
2+3	Total dynamic nominal (with beam loss)	32.00	52.50	71.10	127.90
4	Total dynamic ultimate (with beam loss)	61.00	110.50	151.80	289.30
1+2+3	Grand Total nominal	35.50	56.00	75.50	132.30
1+4	Grand Total ultimate	64.50	114.00	156.20	293.70

HL [W/m] @ 2K per unit length

	β=0.65		β=1	
Cryo duty cycle	4%	8%	4%	8%
HL/m nominal [W/m]	2.90	4.57	5.01	8.78
HL/m ultimate [W/m]	5.27	9.31	10.37	19.50

Input F.Gerigk

Total Heat Loads HP-SPL and cryo-plant

HP-SPL (5 GeV), Total Heat Loads [W] (7 cryomodules β=0.65, 25 cryomodules β=1)

	2K		5-8K		50-75K	
Cryo duty cycle	4%	8%	4%	8%	4%	8%
Static	134	134	580	580	3380	3380
Dynamic nominal	1980	3565	130	260	2180	4360
Dynamic ultimate	4220	8000	130	260	2180	4360

- Installed capacity, for each T level, according to:

  $Q_{installed} = \max\{1.5 \cdot (1.5 \cdot Q_{st} + Q_{dyn.nom.}); 1 \cdot (1.5 \cdot Q_{st} + Q_{dyn.ult})\}$

- **Installed capacity for 4% duty cycle:**

	2K	5-8K	50-75K
Installed Capacities	4423	1500	10870
Equivalent @ 4.5K [kW]	15.8		

Comparable to Yellow Book

- **Installed capacity for 8% duty cycle**

	2K	5-8K	50-75K
Installed Capacities	8207	1690	14140
Equivalent @ 4.5K [kW]	27.8		

1.76 x the value of the Yellow Book

ILC Heat Loads and cryo-plant

TABLE 3.8-2
Main Linac heat loads and cryogenic plant size.

	40-80 K	5-8 K	2 K
Predicted module static heat load (W/mod)	59.19	10.56	1.70
Predicted module dynamic heat load (W/mod)	94.30	4.37	9.68
Modules per cryo unit	192	192	192
Non-module heat load per cryo unit (kW)	1.0	0.2	0.2
Total predicted heat per cryo unit (kW)	30.47	5.07	2.38
Efficiency (fraction Carnot)	0.28	0.24	0.22
Efficiency (Watts/Watt)	16.45	197.94	702.98
Uncertainty & overcapacity factor (Fo)	1.54	1.54	1.54
Heat Load per Cryo Unit including Fo (kW)	46.92	4.72	3.67
Installed power (kW)	771.7	934.9	2577.6
Installed 4.5 K equivalent (kW)	3.5	4.3	11.8
Percent of total power at each level	18.0	21.8	60.2
Total operating power for one cryo unit based on predicted heat (MW)			3.34
Total installed power for one cryo unit (MW)			4.33
Total installed 4.5 K equivalent power for one cryo unit (kW)			19.57

Fo x (Qd+Qs) → [points to the row "Heat Load per Cryo Unit including Fo (kW)"]

Ref. ILC RDR, page III-174

- 1 ILC module = 8 cavities+1 quad (or 9 cavities);
- Cryomodule period ~ 12.7 m
- HL @ 2K:
  - 0.9 W/m (1.26 W/cavity)
  - **5% (4%) of HL of HP-SPL (8% duty cycle)!!**
- Installed capacity @ 4.5K for 1 ILC cryo-unit (**2.5 km**) only 24% more than installed capacity for HP-SPL 8% (**463 m**)

Loads & Capacities at 4.5 K

- We <u>assume</u> the RF loads at 4.5 K are 10 times those at 2.0 K
- We do not include the thermal screen at 5-8 K
- Load at 4.5 K = 10x load at 2.0 K + Load at 5-8 K
- Load at 50-75 K does not change

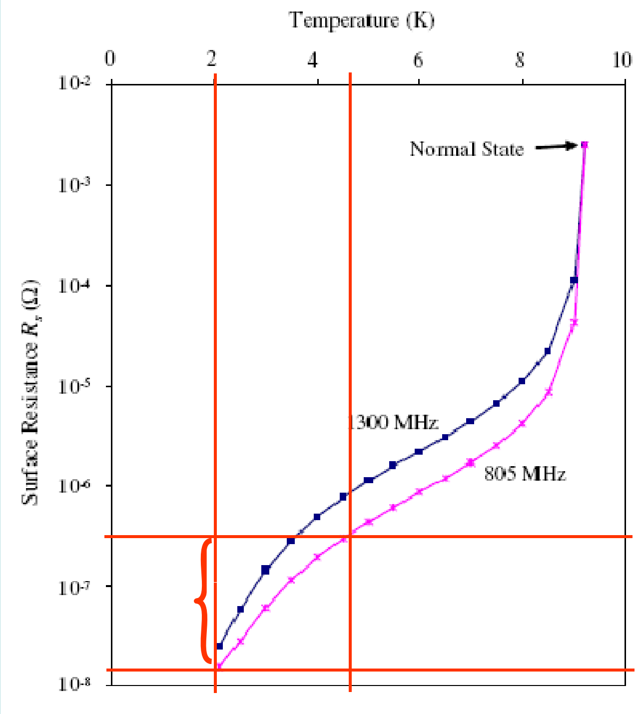


FIG. 3. (Color) RF surface resistances of niobium at 805 and 1300 MHz. 10 nΩ of residual resistances are assumed in this plot.

Ref. Sang-ho Kim & I.Campisi, SNS.

Capacities at 4.5 K and 2.0 K

LP SPL

	T operation	Equiv. capacity at 4.5 K	El. power	Refrigerator cost
	[K]	[kW]	[MW]	[MCHF]
Old data 2007	2.0	2.1	0.8	4.8
Old data 2007	4.5	3.1	1.0	4.8
Actual data	2.0	4.8	1.3	7.5
Actual data	4.5	9.1	2.5	9.5

Revised since presentation from April 07

Capacities at 4.5 K and 2.0 K

HP SPL

	T operation	Equiv. capacity at 4.5 K	El. power	Refrigerator cost
	[K]	[kW]	[MW]	[MCHF]
Yellow Book	2.0	15.8	4.0	15.0
HP SPL 4% duty	2.0	15.8	4.0	15.0
HP SPL 4% duty	4.5	47.2	10.3	24.2
HP SPL 8% duty	2.0	27.8	6.5	21.2
HP SPL 8% duty	4.5	88.0	18.6	35.2

Very uncertain as no reference data exist

Possible cryogenics layout for SPL

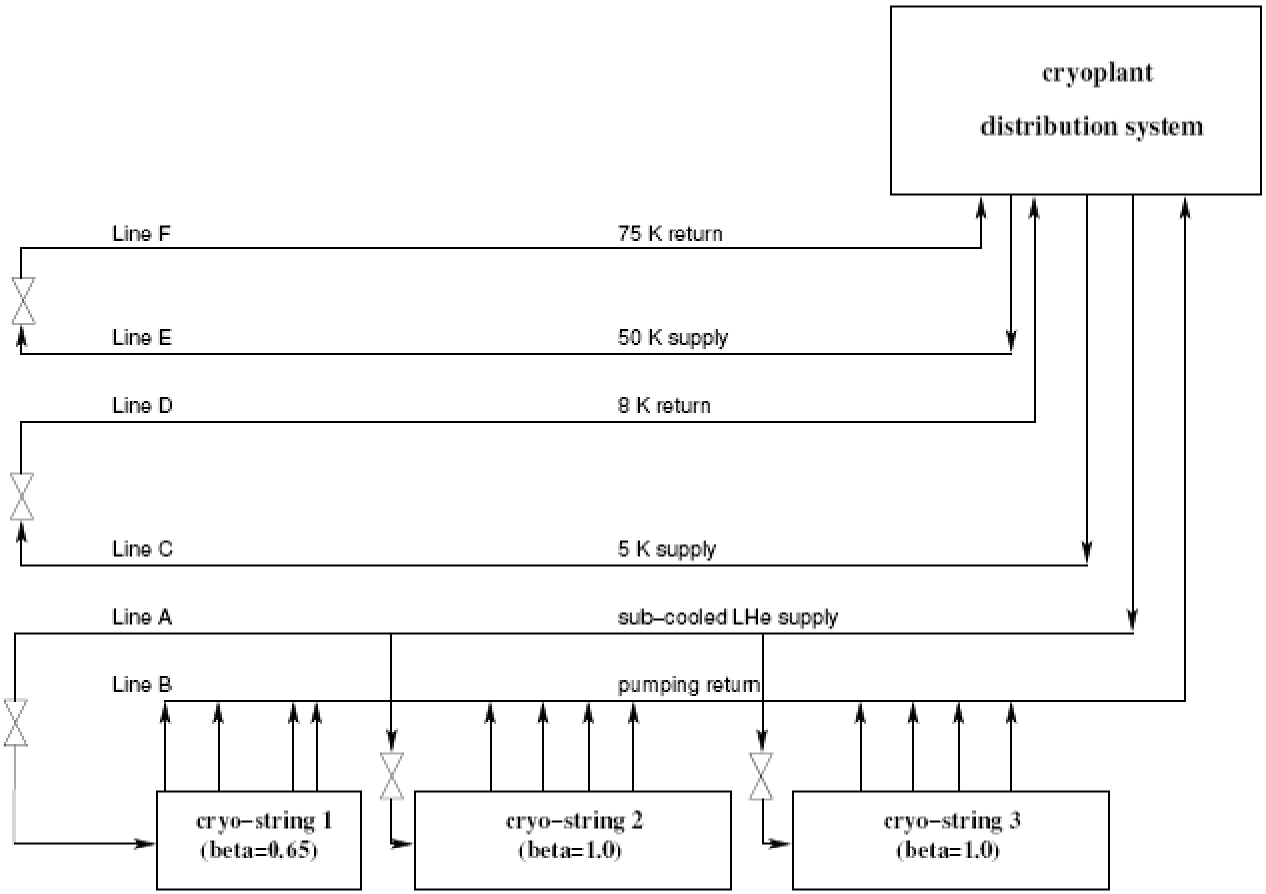


Fig. 4.39: Cooling scheme of the cryogenic system

~10 m (?) shafts

~8 m machine slope

~460 m

1.7% slope

ILC Cryo-scheme and slope

- Laser-striagth ILC:
  slope: 0-0.6%

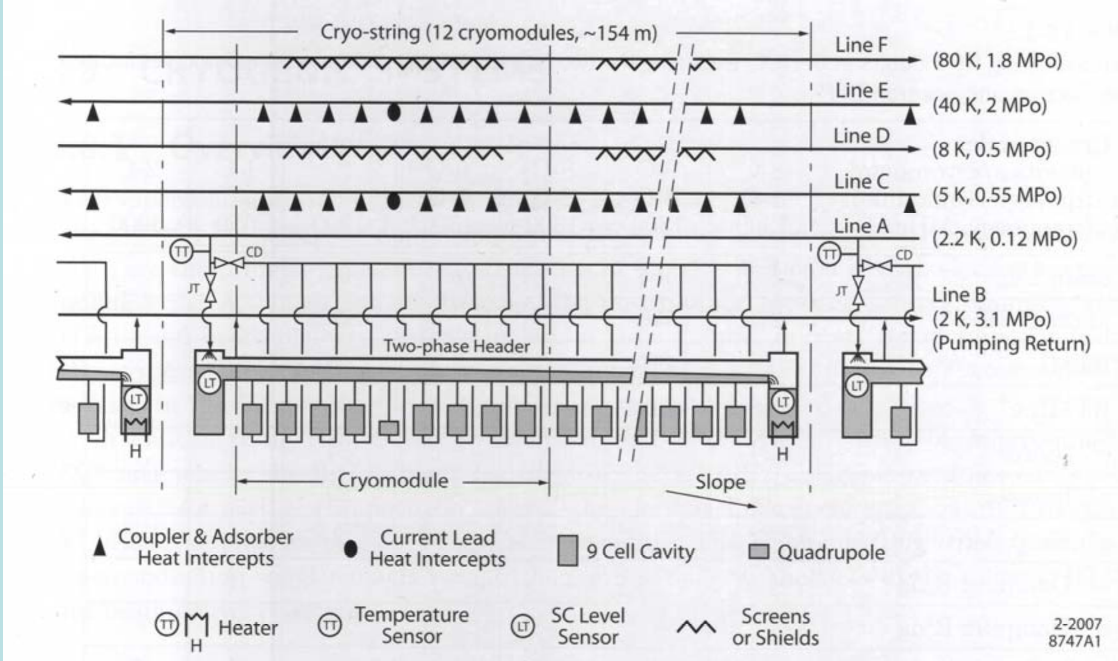
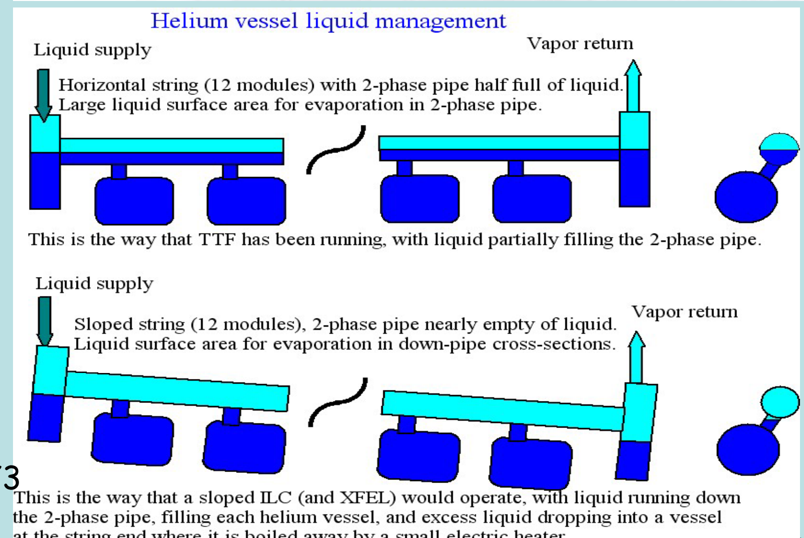


FIGURE 3.8-2. Cooling scheme of a cryo-string.

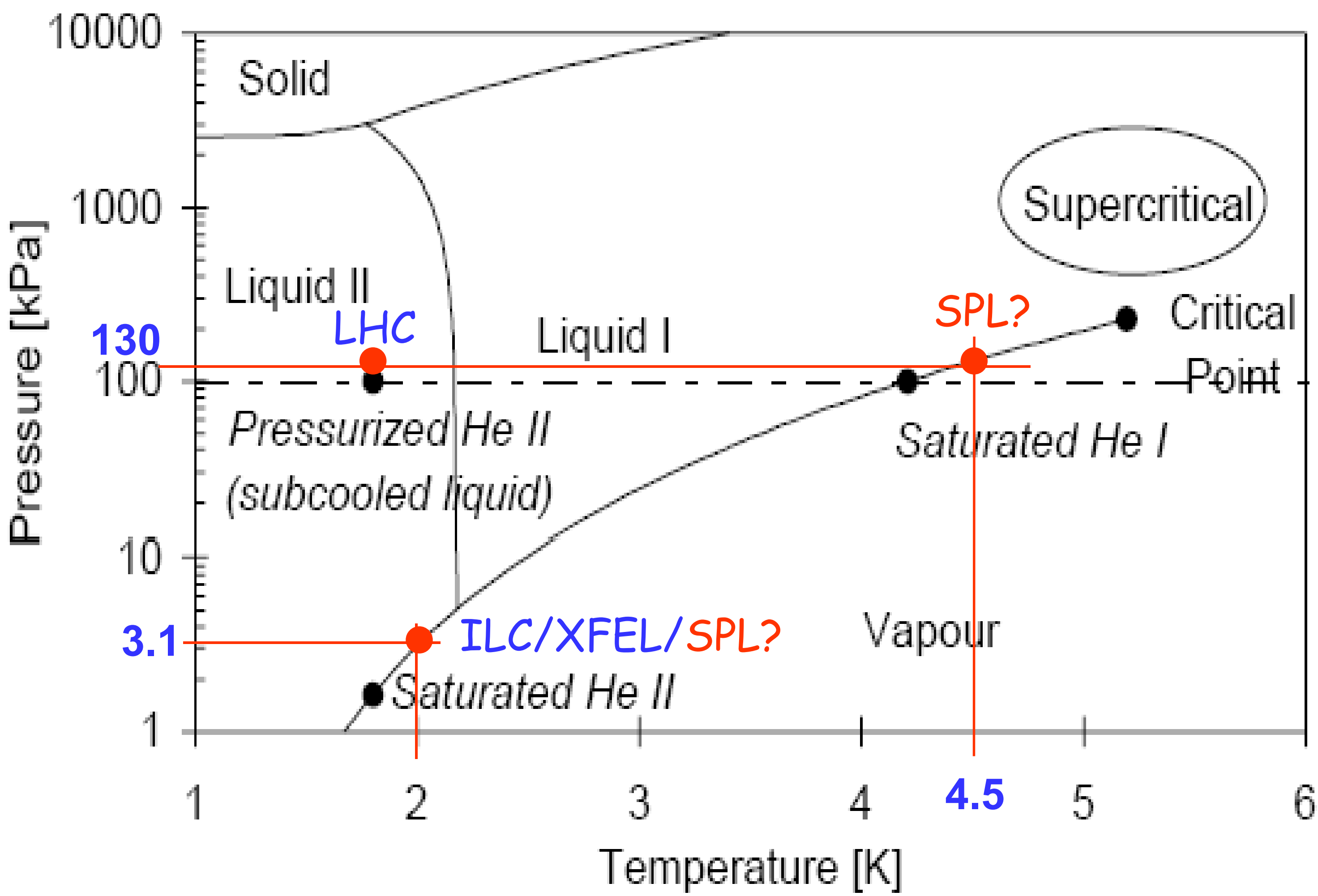
Ref. ILC RDR, page III-172



Ref. ILC RDR, page III-173

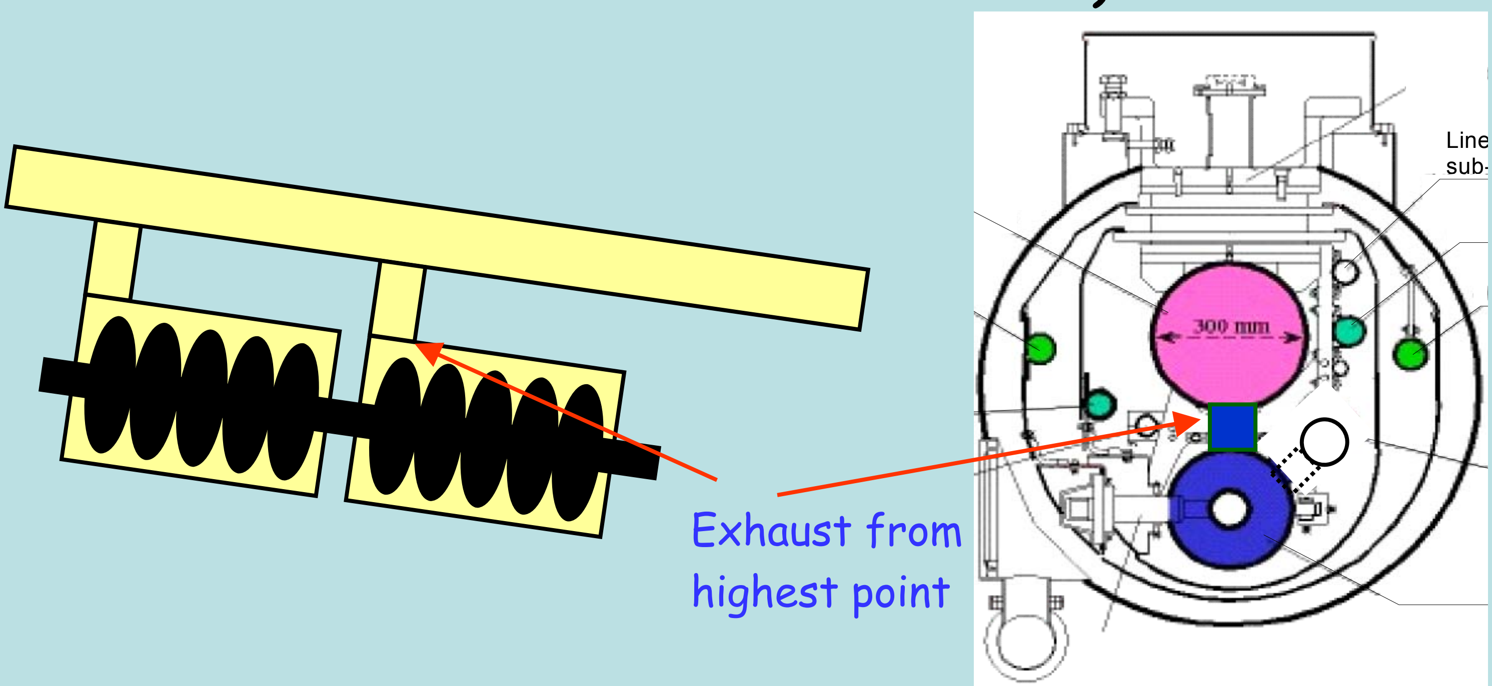
- Similar scheme could be Adopted for SPL

Phase diagram of helium



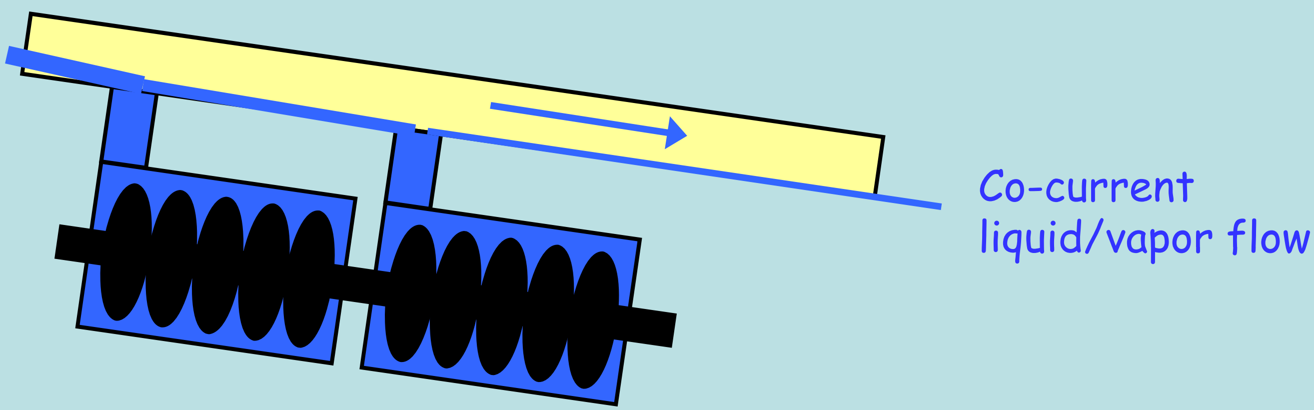
SPL at 4.5K

- 4.5 K pool boiling
  - P=1.3 bars > atm. pressure → prevents helium contamination from air leaks
  - Avoid trapped vapor volumes (slope, cavity wetting…)
  - → cannot re-use ILC/XFEL He vessels)



SPL at 4.5K (cont.d)

- Cooling of cavities
  - Same principle as 2K (ILC)
  - Flow schemes and patterns specific to boiling He → needs further investigation (but as much as ILC does!)



Functions of Gas Return Pipe (line B)

Main function:

- Pumping of low pressure vapors along full cryo unit (~2500m for ILC, 463m for HP-SPL)
  - → Large size for low pressure drop

Additional functions:

- Mechanical function: “backbone in a cryomodule”
  - Tesla/ILC/XFEL…cryomodules all based on this principle
- He expansion buffer volume in case of accidental loss of vacuum (beam or insulation):
  - Design pressure of cavities?
  - Detuning pressure?
- Can it be used as filling line too? To be studied.

Preliminary Sizing of Gas Return Pipe (line B)

Data only for HP SPL as defining factor

	T operation	Pumped mass flow	Line B diameter
	[K]	[g/s]	[mm]
HP SPL 4% duty	2.0	224	300
HP SPL 4% duty	4.5	2300	250
HP SPL 8% duty	2.0	415	350
HP SPL 8% duty	4.5	4300	300

Based on 460 m module string + 200 m line + 20m static head

dp < 10% of p sat for 2K, dp < 5% of p sat for 4.5K

→ **SPL Gas Return Pipe requires ILC-like sizes**

Use of ILC/XFEL cryomodules?

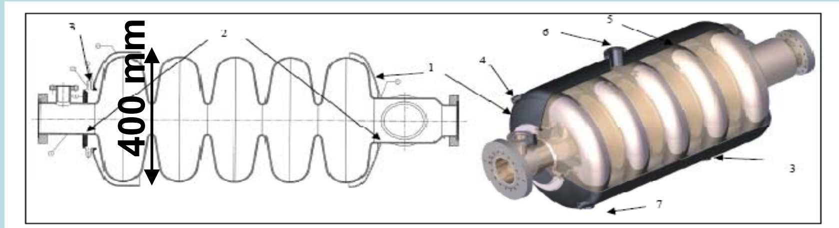
- Design experience? certainly must be exploited:
  - Cryogenic studies (cooling, control & operation issues…)
  - Thermo-mechanical design features
  - Optimization of real-estate gradient
  - …
- Possible use of XFEL H/W ? Yes,…in principle.
- What could be used? Vacuum vessels → yes, …in principle
- Pros:
  - Make use of (future) existing production lines (if timing fits): 2010-2012 ?
  - Profit from economy of scale
- Drawbacks: constraints
  - Frozen design: no flexibility
  - Schedule: we do not get H/W necessarily when we need it

It's too early to decide!

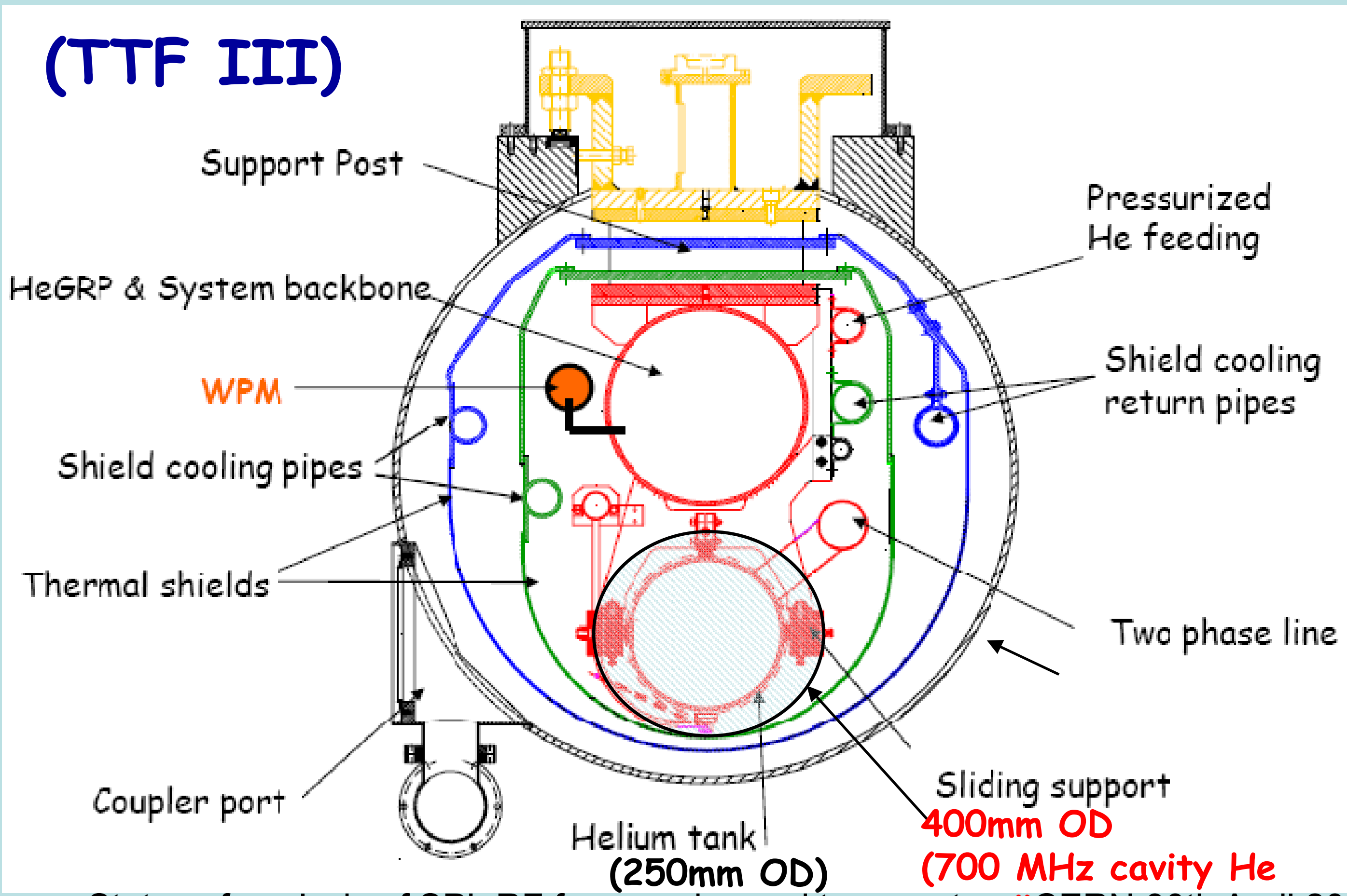
→ <u>Moderate</u> strategy:

- Keep a close eye on XFEL but develop an independent cryomodule design
- Keep as an option
- Possibly reconsider later

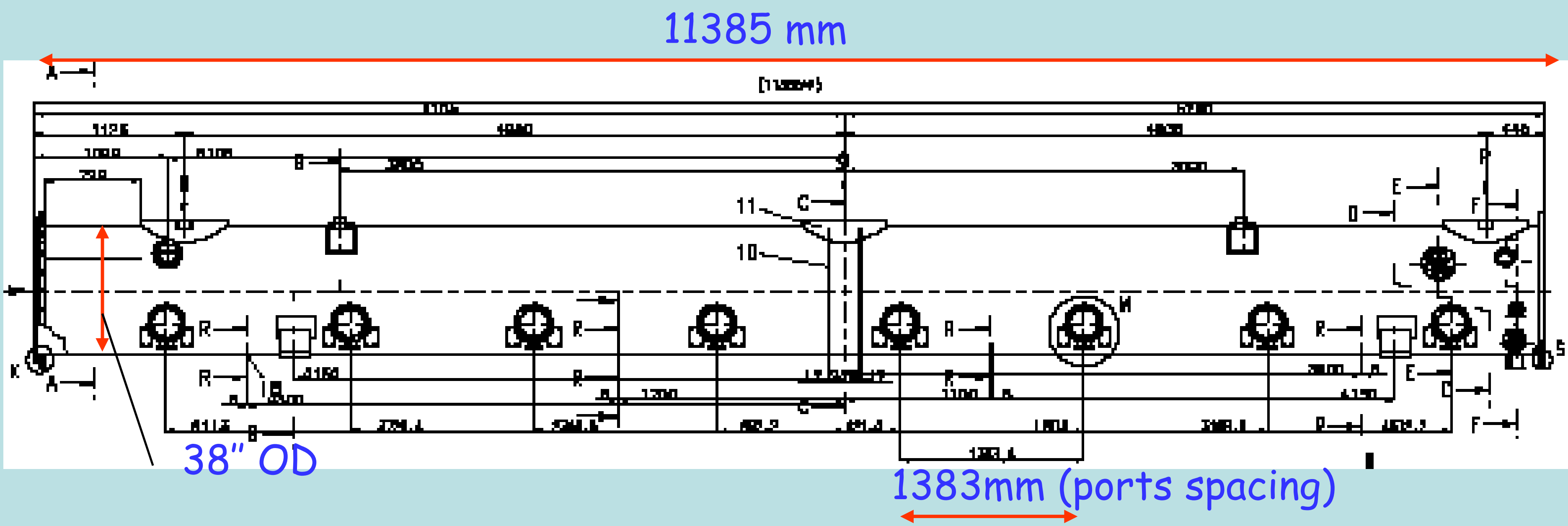
A 704 MHz cavity in an XFEL vessel?



Ref. H. Saugnac et al., "Preliminary Design of a Stainless Steel Helium Tank …", SRF2001, PT022.



XFEL vacuum vessel



Summary I

- If the assumption is correct that:
  4.5 K load = 10 x 2.0 K load

- **4.5 K** operation of the **HP SPL** leads to **very big cryogenic** installations and problems for
  - Surface space
  - Utility supply (electricity , cooling water)
  - Cryogenic installations which in a single unit are uncertain to be manufactured

→ **For HP-SPL, 2.0 K operation seems the only option**

- HP SPL at 2.0 K and 4% duty stays within the frame of the Yellow Book data
- HP SPL at 2.0K and 8% duty needs to be further investigated
  - Do we define an "ultimate" mode
  - How can we install the equipment on the given space

- For the LP SPL 4.5 K operation is an option
  - Less tempting for the new data
- LP SPL operation at 2.0 K would allow to gain experience with 2.0 K operation

Summary II

- SPL Gas Return Pipe requires ILC-like sizes
  - Housing larger 704 MHz cavities for SPL requires specific cryomodule design

- Use of ILC/XFEL experience:
  - Cooling schemes vs. slope, but further studies needed
  - H/W: vac.vessel: wait and see
  - 4.5K helium vessels: SPL specific

Thank you for
your attention

Helium properties

$C_{4.5K}/C_{2K} \approx 1.3$

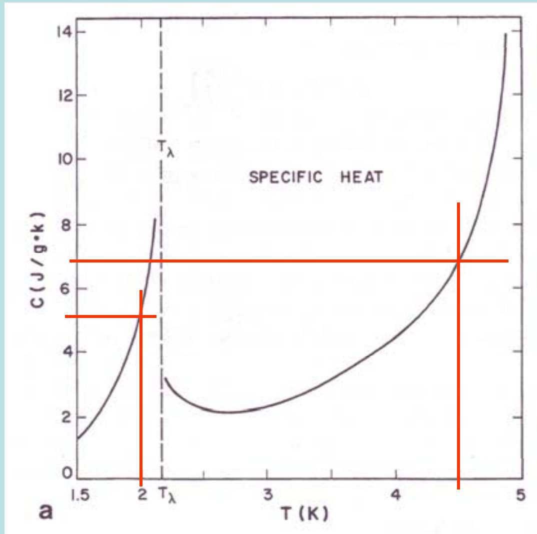


Fig. 3.6a. Specific heat of liquid helium at saturated vapor pressure.

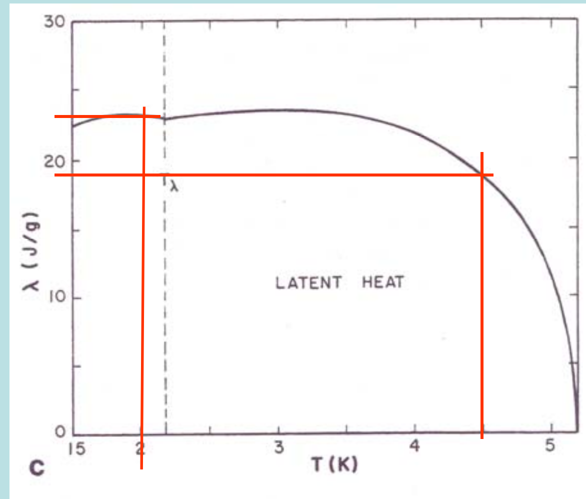
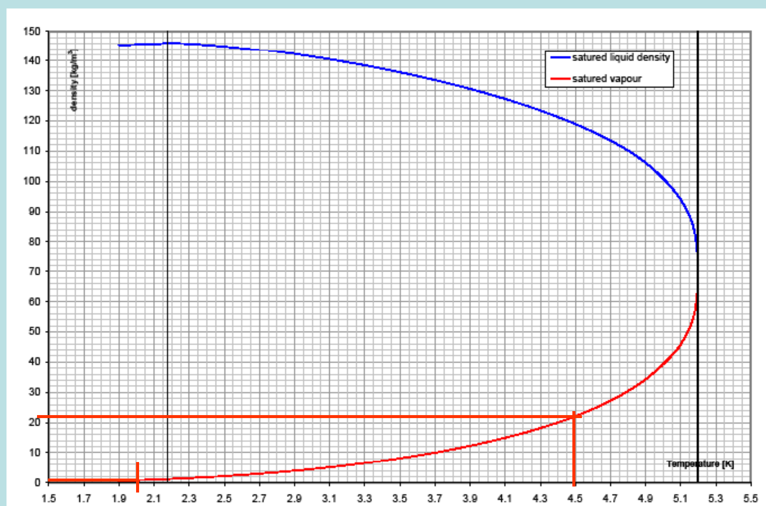


Fig. 3.6c. Latent heat of vaporization of liquid helium.

$\lambda_{4.5K}/\lambda_{2K} \approx 0.8$



Helium density

$\rho_{g4.5K}/\rho_{g2K} \approx 30$

X section of ILC cryomodule

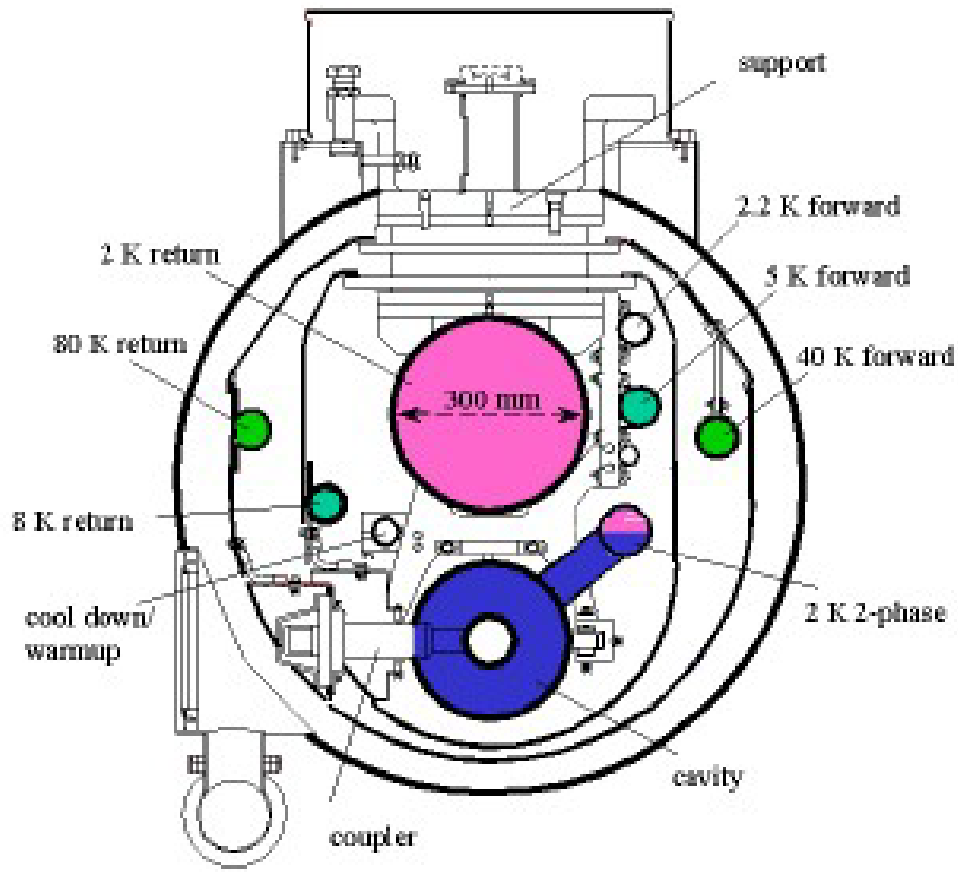


Figure 3.2.11: *Cross section of cryomodule.*