Examples of ILC Cryogenic Systems Cost Optimization

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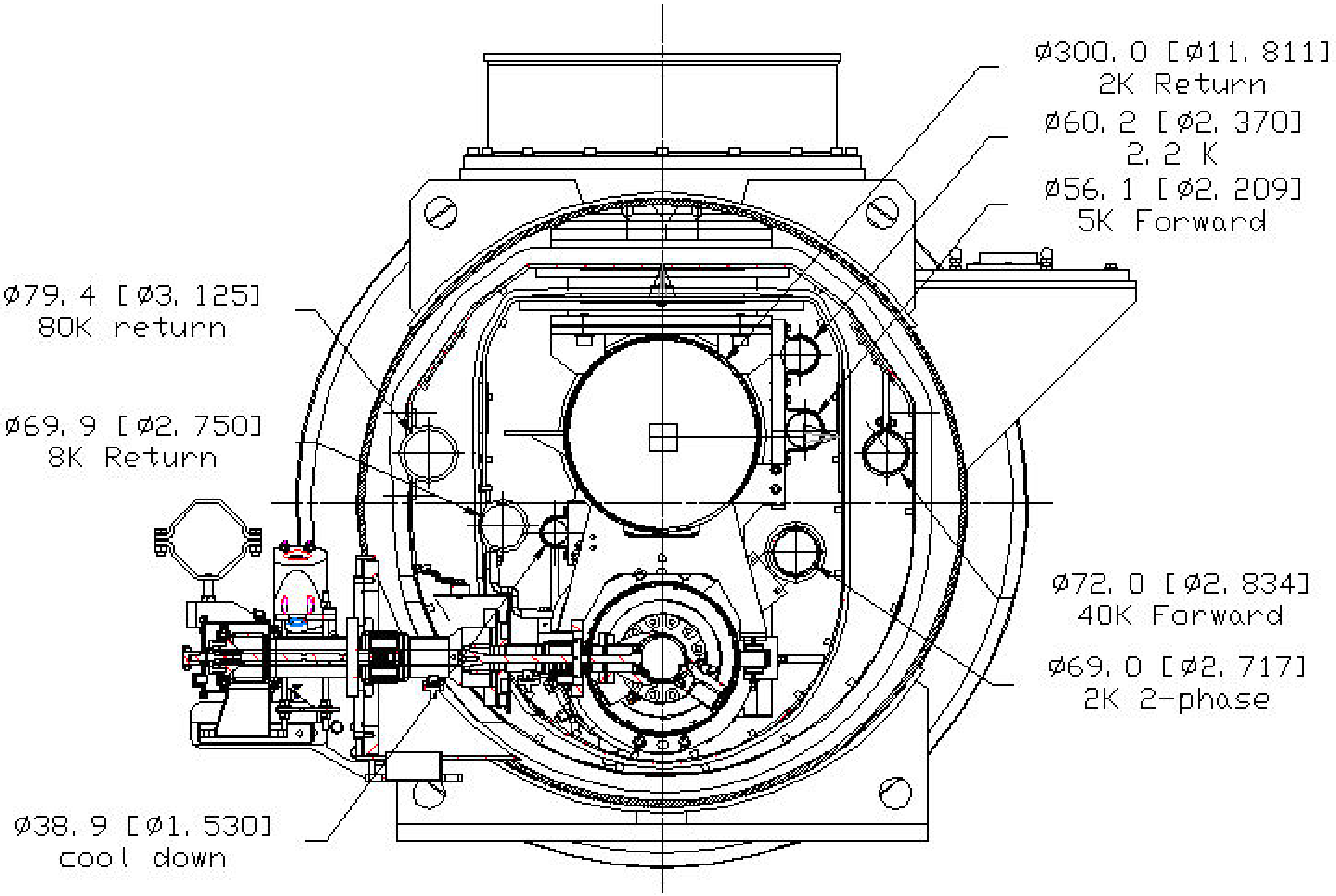
Possibility for Cost Optimization

- Cryomodule / cryogenic system cost trade-off studies
- Costs of the cryomodules per meter are much larger than the costs of the cryogenic system per meter
- Optimization studies for capital and operating costs should consider tradeoffs of cryomodule complexity with heat loads
  - **For example, thermal shields, thermal intercepts, and MLI can perhaps be simplified for efficient production**
  - **At a minimum, the 5 Kelvin thermal shield bridges at cryomodule interconnects can probably be eliminated**

Two examples

- Remove the entire 5 K thermal shield
  - **Retain the 5 K - 8 K piping and thermal intercepts**
- Remove only the 5 K thermal shield bridge at interconnects

Type 4 cryomodule



Heat loads scaled from TESLA TDR

Cryomodule	TESLA	ILC 9-8-9	ILC 8-8-8 and 9-8-9 refers to the number of cavities i
E, [MV/m]	23.4	31.5	G
Q	1.E+10	1.E+10	
Rep rate, [Hz]	5	5	
Number of Cavities	12	8.667	avg number of cavities per module
Fill time [µsec]	420	597	Tf
Beam pulse [µsec]	950	969	Tb
Number of bunches	2820	2670	Nb
Particles per bunch [1e10]	2	2.04	Qb
Gfac		2.09	Stored Energy Factor = G^2*(Tb + 1.1*Tf)
Pfac		1.54	Input Power Factor = G*(Tb + 2*Tf)*Cfac
Bfac		0.99	Bunch Factor = Nb*Qb^2
Cfac		0.95	Beam Current Factor = Qb*Nb/Tb

Module predicted heat loads -- 5K

With removal of 5 K thermal shield, radiative load goes down to 2 K level

	TESLA		ILC 9-8-9		
	5K		5K		
Radiation	1.95		1.41		Static load scaled by number of cavities
Supports	2.40		2.40		Assume indepent of nuimber of cavities
Input coupler	2.05	1.19	1.48	1.32	Static load scaled by number of cavities, dynamic by Pfac also
HOM coupler (cables)	0.40	2.66	0.29	1.82	Static and dynamic load scaled by number of cavities, dynamic by Cfac alsc
HOM absorber	3.13	0.77	3.13	0.76	Dynamic load scaled by Bfac
Current leads			0.47	0.47	Weigh by a factor of 1/3 since only 1 in 3 modules have quads**
Diagnostic cable	1.39	-	1.39	-	Assume independent of nuimber of cavities
Scales as Pfac		1.19		1.32	
Independent of G,Tf	11.32	3.43	10.56	3.04	
Static, dynamic sum	11.32	4.62	10.56	4.37	Total for 9-8-9 RF unit below
5K Sum [W]	**15.9**		**14.9**		44.80

Retain the 5 K - 8 K helium circuit for thermal intercepts

Module predicted heat loads -- 2K

Additional 1.41 W static heat

Temperature Level	TESLA 2K (static)	TESLA 2K (dynamic)	ILC 9-8-9 2K (static)	ILC 9-8-9 2K (dynamic)	
RF load		4.95		7.46	Dynamic load scaled by the number of cavities and Gfac
			1.41		Taking thermal radiation to 2 K, no 5 K shield
Supports	0.60		0.60	-	Assume independent of nuimber of cavities
Input coupler	0.76	0.14	0.55	0.16	Static load scaled by number of cavities, dynamic by Pfac also
HOM coupler (cables)	0.01	0.27	0.01	0.18	Static and dynamic load scaled by number of cavities, dynamic by Cfac alsc
HOM absorber	0.14	0.02	0.14	0.01	Dynamic load scaled by Bfac
Beam tube bellows		0.24		0.36	Dynamic load scaled by the number of cavities and Gfac
Current leads	0.04		0.28	0.28	Weigh by a factor of 1/3 since only 1 in 3 modules have quads**
HOM to structure		1.68		1.20	Static load scaled by the number of cavities, dynamic by Bfac also
Coax cable (4)	0.05		0.05		Assume indepent of nuimber of cavities
Instrumentation taps	0.07		0.07		Assume indepent of nuimber of cavities
Scales as Gfac		5.19		7.83	
Scales as Pfac		0.14		0.16	
Independent of G,Tf	1.67	1.97	3.11	1.68	
Static, dynamic sum	1.67	7.30	3.11	9.66	Total for 9-8-9 RF unit below
2K Sum [W]	9.0		12.8		38.30

Note: implied is a pessimistic assumption that view factor of 2 K objects is as large as 5 K thermal shield

Module predicted heat loads -- 40K

No significant change

	TESLA 40K		ILC 9-8-9 40K		
Radiation	44.99		32.49		Static load scaled by number of cavities
Supports	6.00		6.00		Assume indepent of nuimber of cavities
Input coupler	21.48	59.40	15.51	66.08	Static load scaled by number of cavities, dynamic by Pfac also
HOM coupler (cables)	2.55	13.22	1.84	9.04	Static and dynamic load scaled by number of cavities, dynamic by Cfac alsc
HOM absorber	(3.27)	15.27	(3.27)	15.04	Dynamic load scaled by Bfac
Current leads			4.13	4.13	Weigh by a factor of 1/3 since only 1 in 3 modules have quads**
Diagnostic cable	2.48		2.48		Assume indepent of nuimber of cavities
Scales as Pfac		59.40		66.08	
Independent of G,Tf	74.23	28.49	59.19	28.22	
Static, dynamic sum	74.23	87.89	59.19	94.30	Total for 9-8-9 RF unit below
40K Sum [W]	**162.1**		**153.5**		460.46

Cryogenic unit parameters

With 5 K thermal shield

		40 K to 80 K	5 K to 8 K	2 K
Predicted module static heat load	(W/module)	59.19	10.56	1.70
Predicted module dynamic heat load	(W/module)	94.30	4.37	9.66
Number of modules per cryo unit (8-cavity modules)		192.00	192.00	192.00
Non-module heat load per cryo unit	(kW)	1.00	0.20	0.20
Total predicted heat per cryogenic unit	(kW)	30.47	3.07	2.38
Heat uncertainty factor on static heat (Fus)		1.10	1.10	1.10
Heat uncertainty factor on dynamic heat (Fud)		1.10	1.10	1.10
Efficiency (fraction Carnot)		0.28	0.24	0.22
Efficiency in Watts/Watt	(W/W)	16.45	197.94	702.98
Overcapacity factor (Fo)		1.40	1.40	1.40
Overall net cryogenic capacity multiplier		1.54	1.54	1.54
Heat load per cryogenic unit including Fus, Fud, and Fo	(kW)	46.92	4.72	3.67
Installed power	(kW)	771.72	934.91	2577.65
Installed 4.5 K equiv	(kW)	3.53	4.27	11.78
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)			4.28	
Total installed 4.5 K equivalent power for one cryo unit (kW)			19.57	

Cryogenic unit parameters

No 5 K thermal shield

		40 K to 80 K	5 K to 8 K	2 K
Predicted module static heat load	(W/module)	59.19	9.16	3.11
Predicted module dynamic heat load	(W/module)	94.30	4.37	9.66
Number of modules per cryo unit (8-cavity modules)		192.00	192.00	192.00
Non-module heat load per cryo unit	(kW)	1.00	0.20	0.20
Total predicted heat per cryogenic unit	(kW)	30.47	2.80	2.65
Heat uncertainty factor on static heat (Fus)		1.10	1.10	1.10
Heat uncertainty factor on dynamic heat (Fud)		1.10	1.10	1.10
Efficiency (fraction Carnot)		0.28	0.24	0.22
Efficiency in Watts/Watt	(W/W)	16.45	197.94	702.98
Overcapacity factor (Fo)		1.40	1.40	1.40
Overall net cryogenic capacity multiplier		1.54	1.54	1.54
Heat load per cryogenic unit including Fus, Fud, and Fo	(kW)	46.92	4.31	4.08
Installed power	(kW)	771.72	852.48	2870.38
Installed 4.5 K equiv	(kW)	3.53	3.89	13.11
Percent of total power at each level		17.2%	19.0%	63.9%
Total operating power for one cryo unit based on predicted heat (MW)			3.50	
Total installed power for one cryo unit (MW)			4.49	
Total installed 4.5 K equivalent power for one cryo unit (kW)			20.54	

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

5 K thermal shield cost data

- LHC
  - **Thermal shield for dipole cryostats was $550/meter (M&S only)**
    - A bit simpler than ILC cryomodule 5 K and 40 K thermal shields since not so many feedthroughs
    - Input couplers are a complication for ILC
    - MLI not included
  - **MLI cost is about $130/m**
  - **So with MLI M&S is about $680/m or $8600 per cryomodule**

5 K thermal shield cost estimates

- Industrial cost estimate
  - **M&S estimate for 5 K shield including MLI is $4000**
  - **Installation labor is estimated at $1700**
- Fermilab cost estimate
  - **M&S estimate for 5 K shield including MLI is $5900 based on US LHC costs**
- Shield cost conclusion
  - **Average the two estimates and LHC costs**
  - **Total cost is $6200 M&S + $1700 labor = $7900 per cryomodule**

Result of preliminary analysis

- Removal of 5 K thermal shield results in M&S savings of $7900 (shield) - $4200 (cryo) = $3700 per cryomodule
- Operating costs increase by about $770 per cryomodule per year
  - **Payback for 5 K shield is about 5 years**
- It may end up close to "break-even" or difficult to identify a definite cost advantage
  - **In general, with several alternatives which satisfy system requirements and show no clear cost difference, the "tie-breaking" criterion should be to take the simpler approach**

Next steps -- refine analysis

- Investigate thermal shield cost
  - **LHC experience and estimates differ**
  - **Assembly labor also uncertain**
  - **Secondary benefits of simplification not counted**
- Investigate real addition to 2 K heat
  - **Assumed same view factor to 2 K system as to 5 K shield, which is pessimistic**
- Consider alternative warm thermal shield temperatures with absence of 5 K shield

5 K thermal shield bridge removal

- Removal of the 5 K thermal shield bridge from the cryomodule interconnects should provide net gain
  - **Length is ~800 mm, and thermal impact scales with shield length removed = 0.8/12.65**
  - **Impact on cryoplant M&S is no more than 0.063 x $4200 = $270 added cryogenic system M&S per cryomodule**
    - Less since little at 2 K in interconnect
  - **Impact on operating costs is 0.063 x $770 = $50 per cryomodule per year**
- Shield bridge interferes with pipe interconnect bellows and is labor-intensive to install, so cost is more than the per meter shield cost
  - **Cost more than $500 per cryomodule**
- Result is net savings for leaving out the 5 K thermal shield bridge at interconnects even after 5 years

Cryomodule/cryogenics optimization is a Work Package

- Work package #9 in Cryogenic Systems list
  - **High priority**
  - **A joint task with cryomodules**
  - **Norihito Ohuchi responsible for KEK effort on this topic**
    - KEK may do tests at STF regarding the 5 K thermal shield in addition to analysis
  - **Vittorio Parma responsible for CERN effort**
    - Will consist of input from LHC experience
    - One input already -- LHC eliminated their 5 K thermal shield after a similar study
  - **Tom Peterson will coordinate Fermilab effort for this work package**