ILC Cryogenic Systems Reference Design

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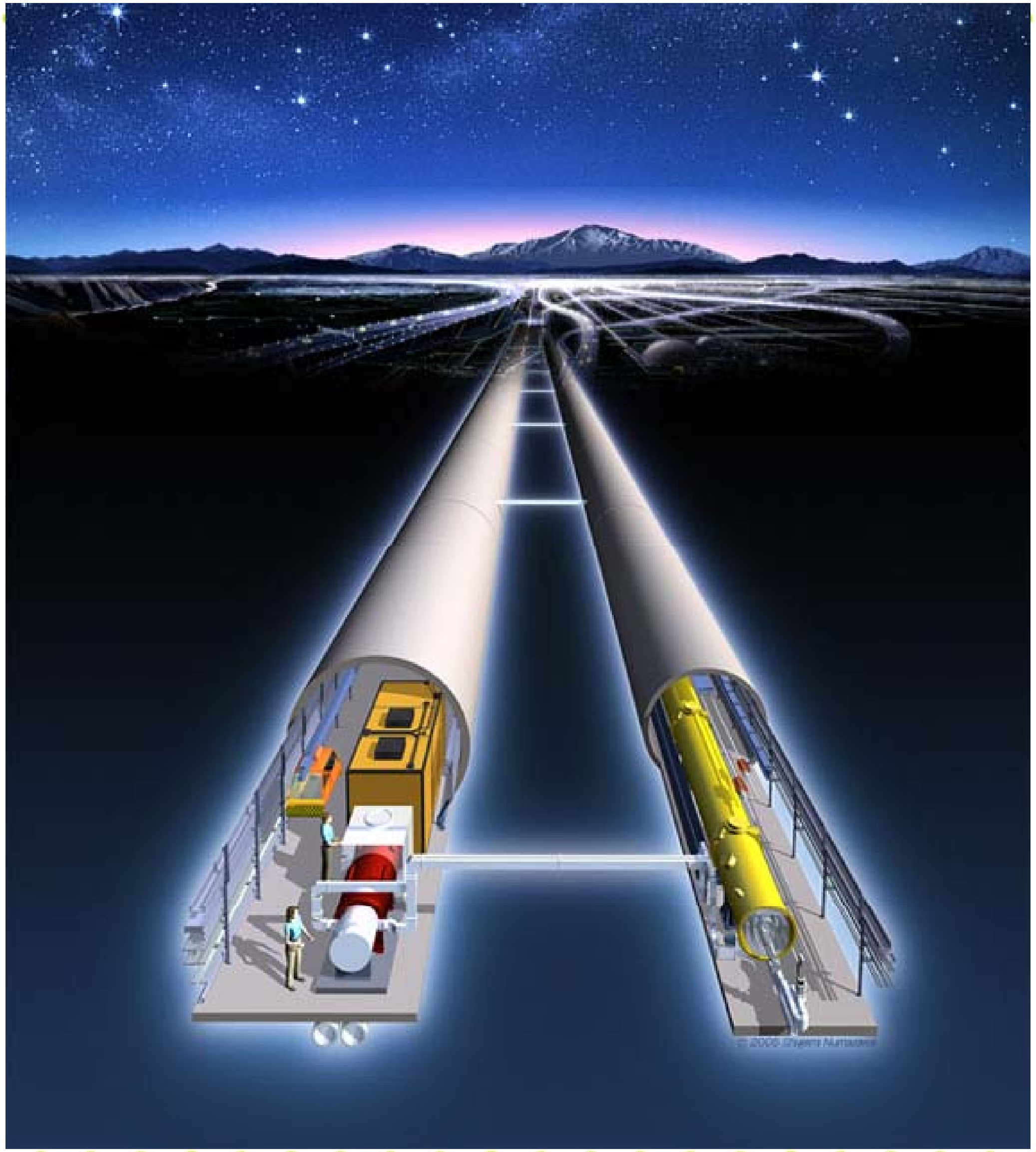
20 July 2007

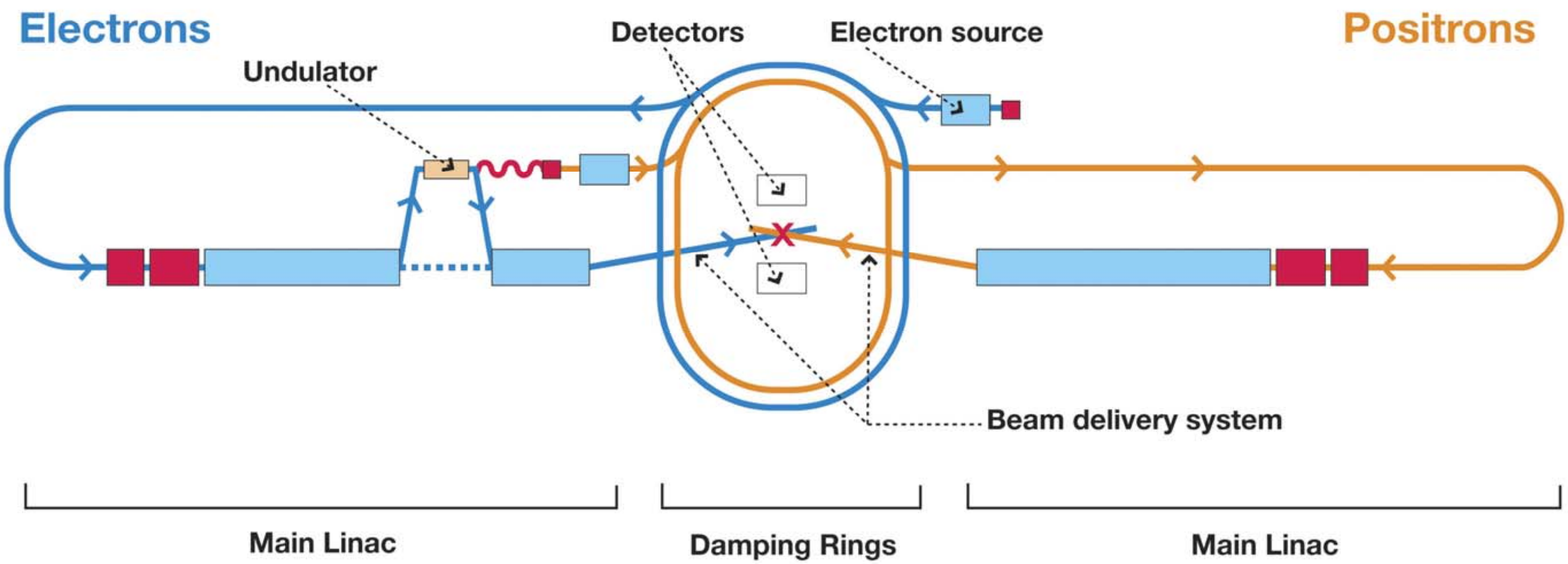
Reference Design

- A “Global Design Effort” (GDE) began in 2005 to study a TeV scale electron-positron linear accelerator based on superconducting radio-frequency (RF) technology, called the International Linear Collider (ILC).
- In early 2007, the design effort culminated in a “Reference Design” for the ILC, closely based on the earlier TESLA design.
- This presentation and associated paper present some of the main features of the reference design for the cryogenic system.

International Linear Collider

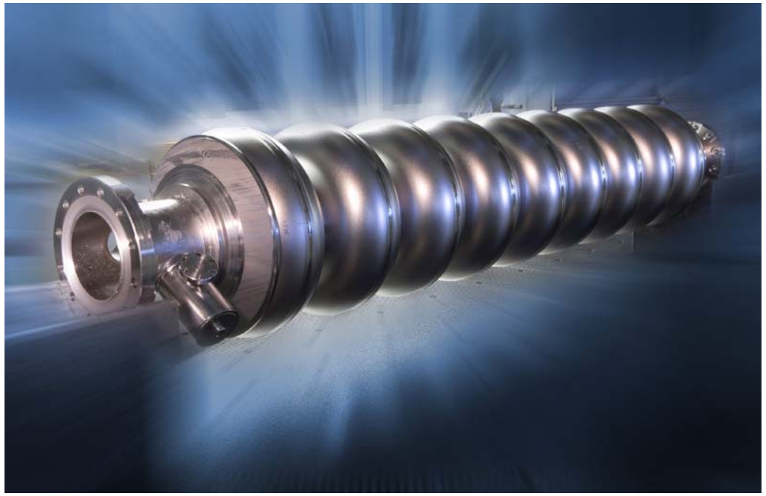


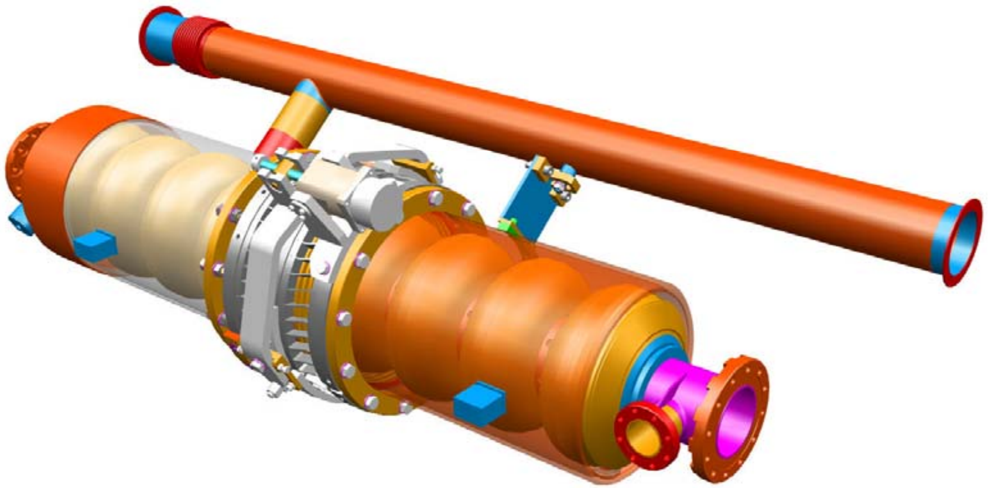
International Linear Collider



- Each linac is about 14 km long
- Damping rings about 6.7 km circumference

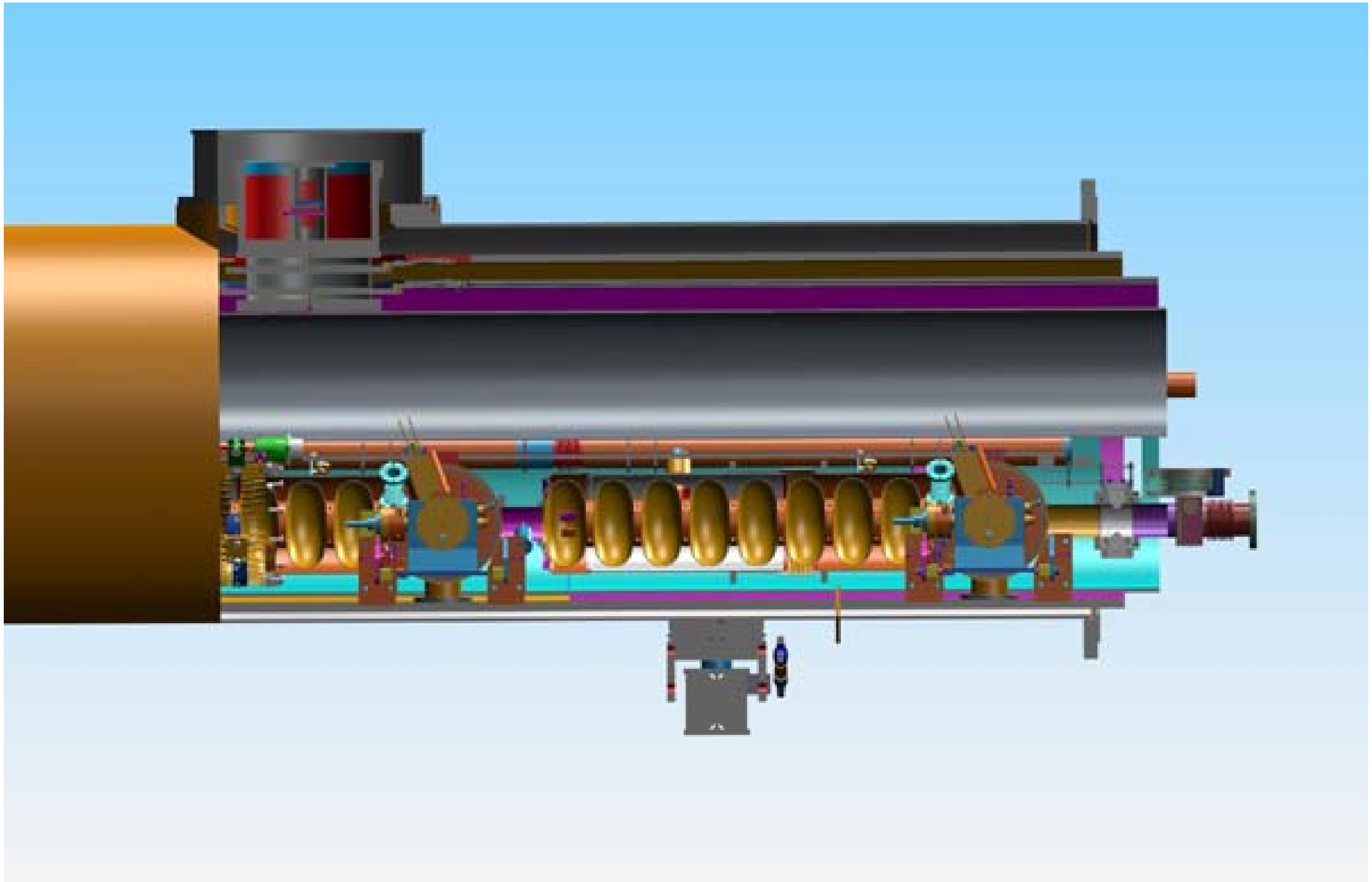
9 cell niobium RF cavity





- 9-cell niobium RF cavities are welded into titanium helium vessels
- Eight (or nine) of these “dressed” cavities are assembled into a cryostat called a “cryomodule”

Main linac cryomodule



Cryomodule from TESLA TDR

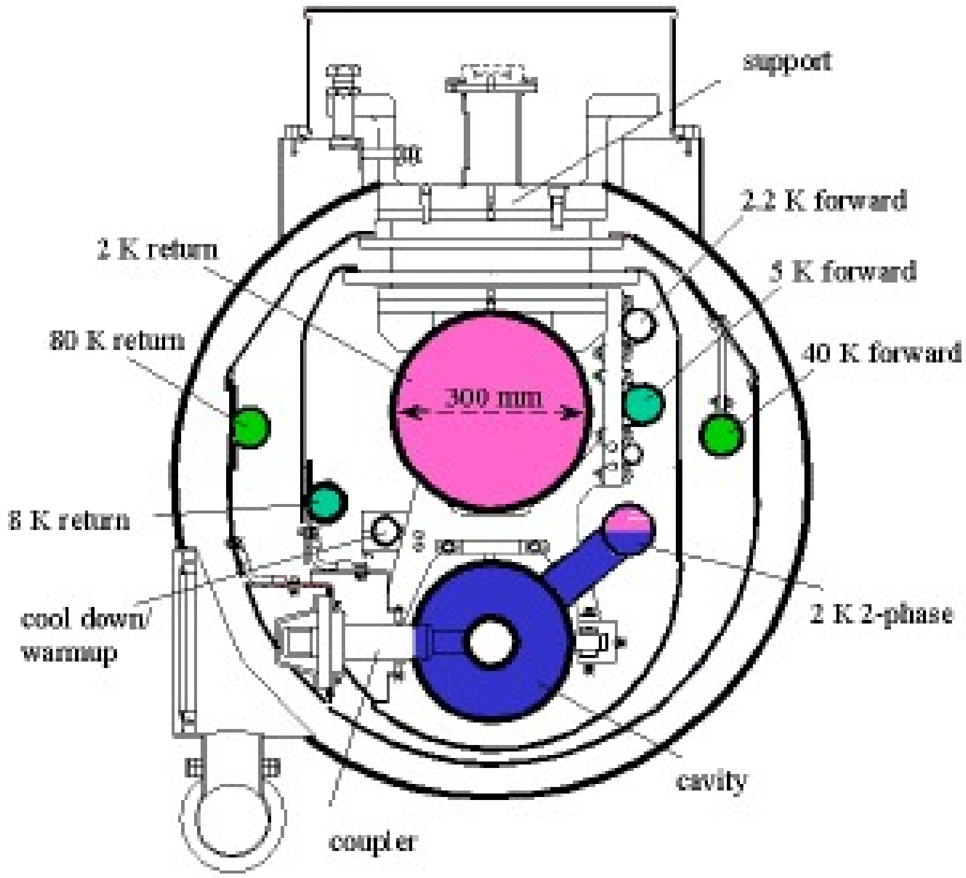


Figure 3.2.11: *Cross section of cryomodule.*

Cryomodule on test stand at DESY

ILC RF cryomodule count

Cryomodules	8-cavity 1 quad	9-cavity no quad	8-cavity 2-quad	6-cavity 6-quad*	1300 MHZ	1-cavity 650 MHZ	2-cavity 3900 MHZ
Main Linac e-	282	564			846		
Main Linac e+	278	556			834		
RTML e-	18	30			48		
RTML e+	18	30			48		
e- source	17	8			25		
e+ booster	12		6	4	22		
e+ Keep Alive	2				2		
e- damping ring						18	
e+ damping ring						18	
beam delivery system							2
TOTAL	627	1188	6	4	1825	36	2

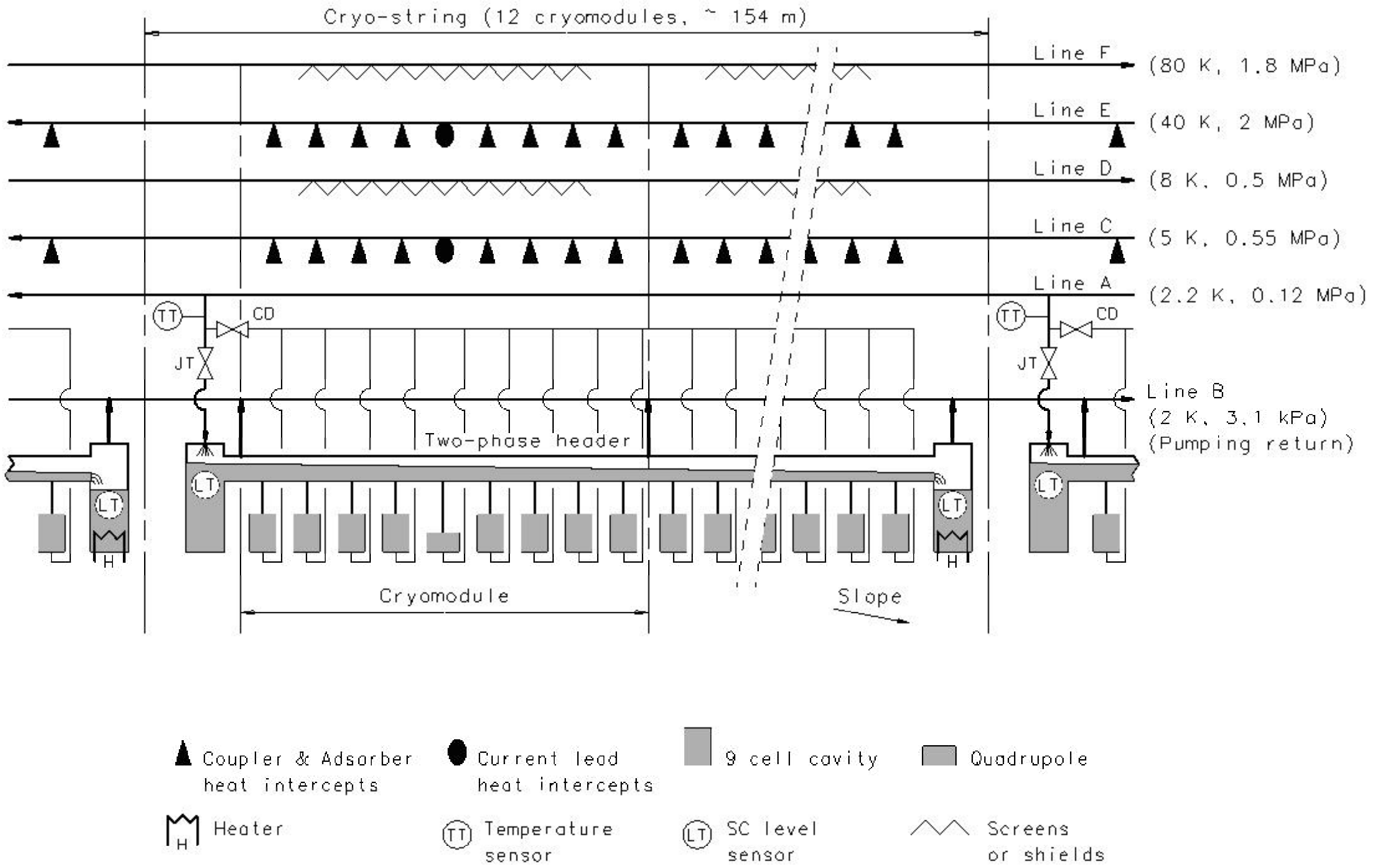
* I would make these 3 cavities and 3 quads per module and double the number of modules

- Above are installed numbers, not counting uninstalled spares

ILC superconducting magnets

- About 640 1.3 GHz modules have SC magnets
- Other SC magnets are outside of RF modules
  - 290 meters of SC helical undulators, in 2 - 4 meter length units, in the electron side of the main linac as part of the positron source
  - In damping rings -- 8 strings of wigglers (4 strings per ring), 10 wigglers per string x 2.5 m per wiggler
  - Special SC magnets in sources, RTML, and beam delivery system

A cryogenic “string”



Main Linac Layout - 1

modules	without quad	with quad	without quad
RF unit (lengths in meters)	12.652	12.652	12.652

three modules

	RF unit	RF unit	RF unit	RF unit	end box
string (vacuum length)	37.956	37.956	37.956	37.956	2.500

twelve modules plus string end box

	string	string	string	string
possible segmentation unit	154.324	154.324	154.324	154.324

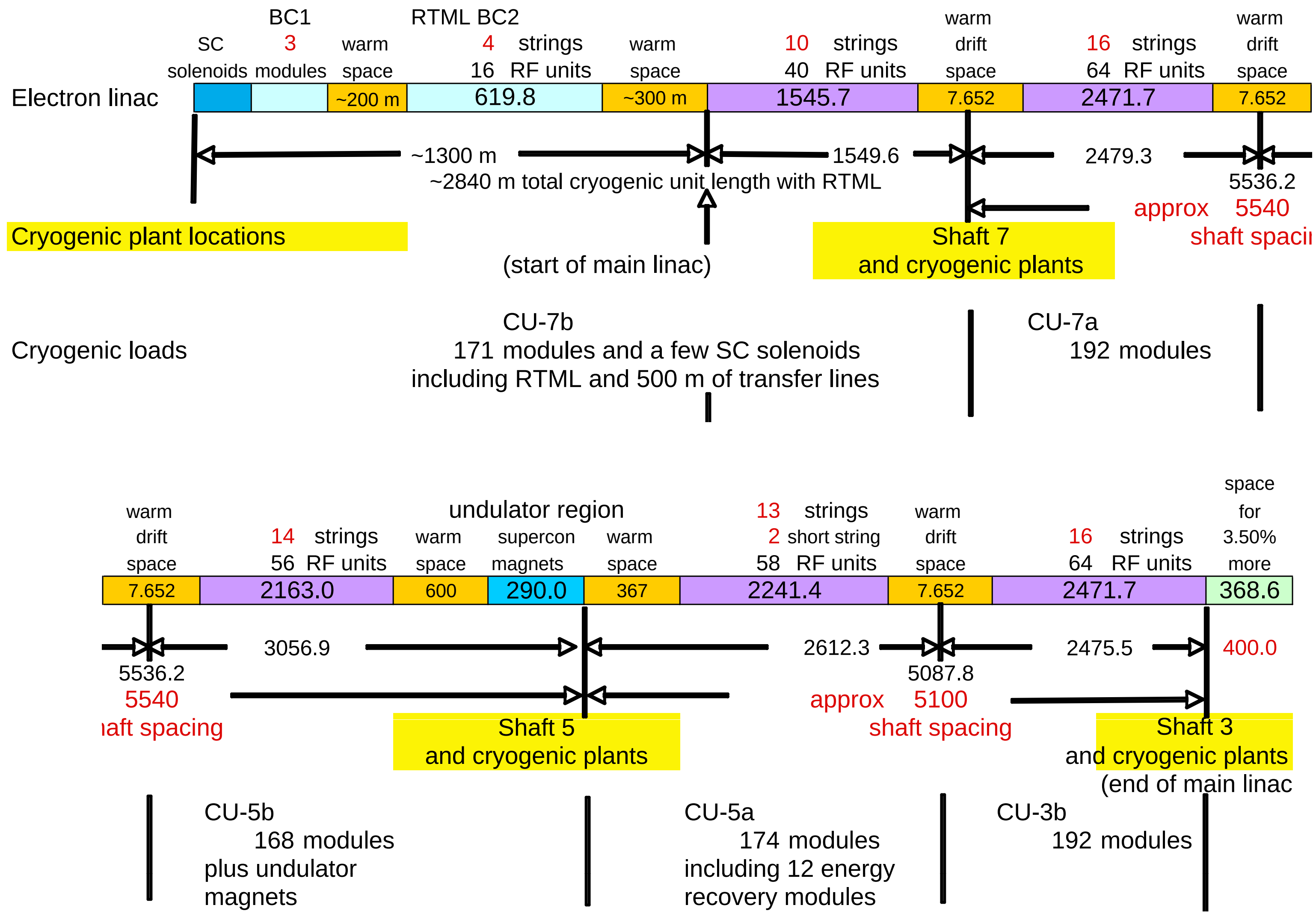
48 modules
(segmentation box is the same as string end box (2.5 m) and all contain vacuum breaks)

	service box end	segment	segment	segment	segment	service box end
Cryogenic Unit **(16 strings)**	2.500	617.296	617.296	617.296	614.796	2.500

(1 cryogenic unit = 192 modules = 4 segments*48 CM with string end boxes plus service boxes.)

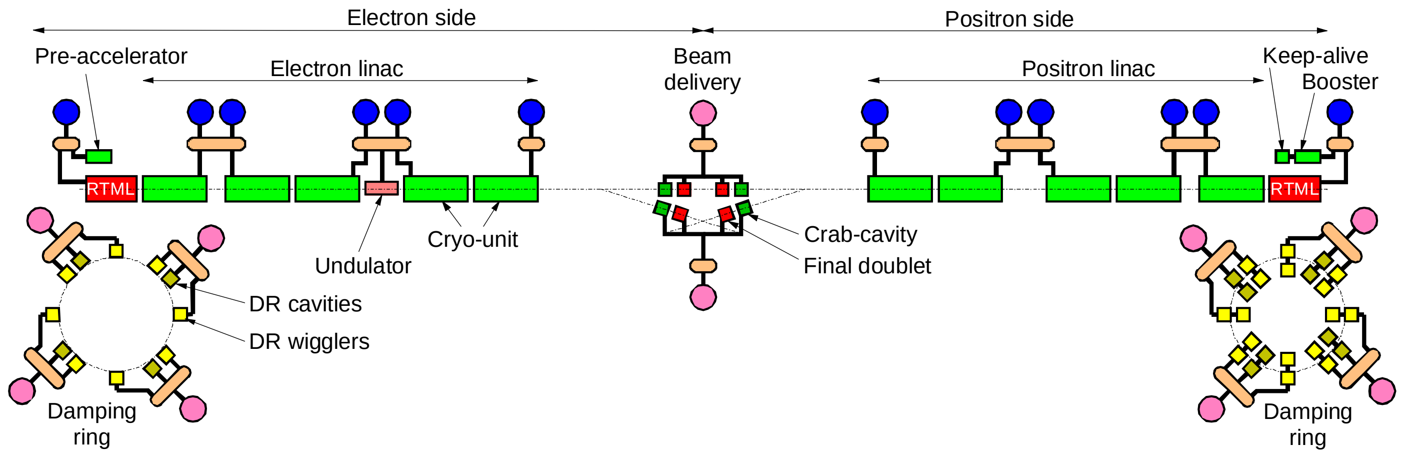
2471.7 meters

Main Linac Layout - 2

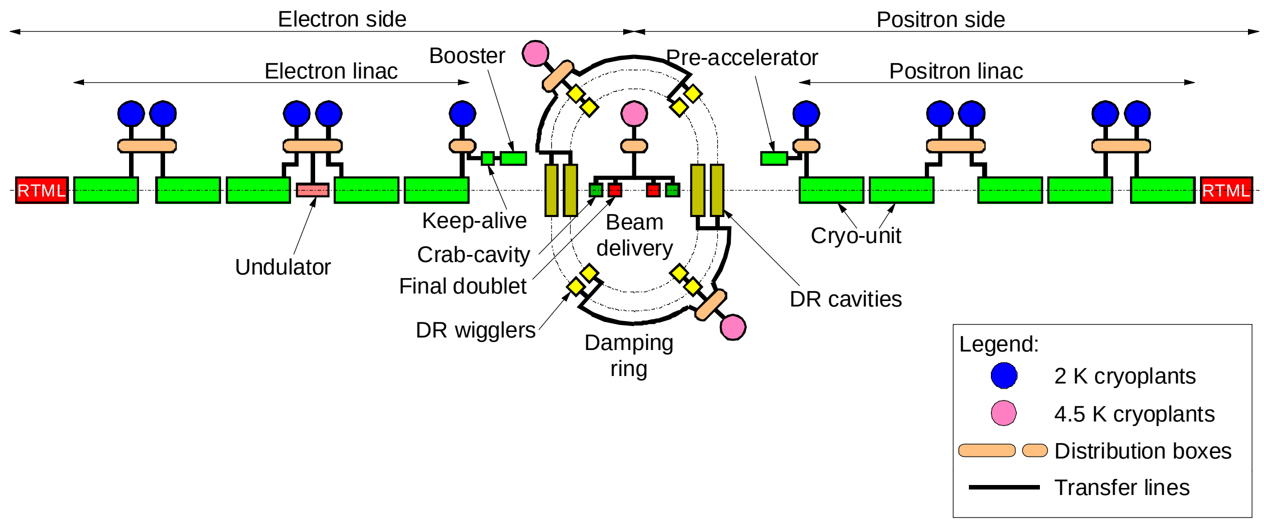


Cryogenic plant arrangement

Baseline Configuration Layout



Reference Design Layout



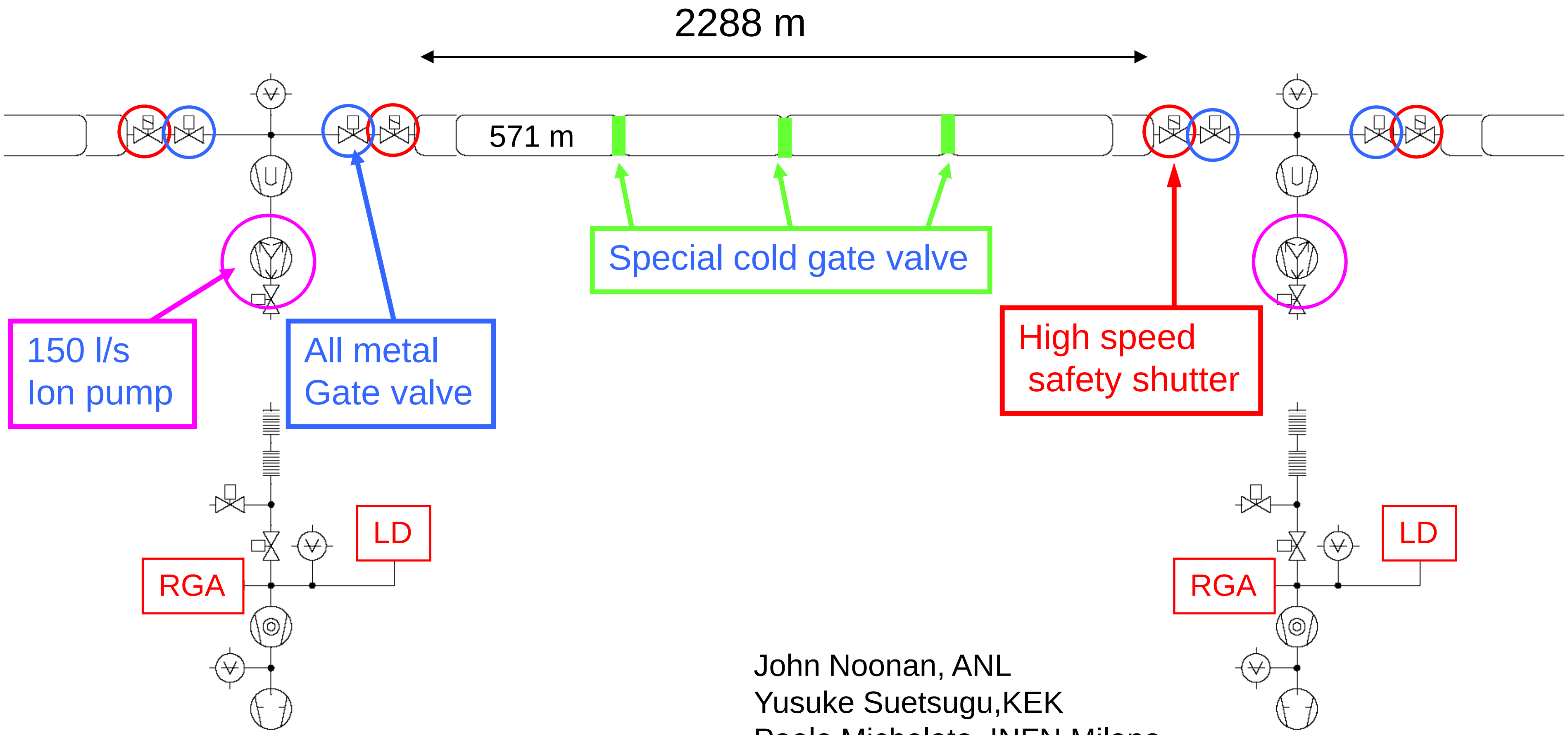
Major cryogenic distribution components

- 6 large (2 K system) tunnel service or "distribution" boxes
  - Connect refrigerators to tunnel components and allow for sharing load between paired refrigerators
- 20 large (2 K) tunnel cryogenic unit "feed" boxes
  - Terminate and/or cross-connect the 10 cryogenic units
- ~132 large (2 K) string "connecting" or string "end" boxes of several types
  - Contain valves, heaters, liquid collection vessels, instrumentation, vacuum breaks
  - Note that these have many features of modules!
- ~3 km of large transfer lines (including 2 Kelvin lines)
- ~100 "U-tubes" (removable transfer lines)
- Damping rings are two 4.5 K systems
  - Various distribution boxes and ~7 km of small transfer lines
- BDS and sources include transfer lines to isolated components
- Various special end boxes for isolated SC devices

Cryogenic unit length limitations

- **25 KW total equivalent 4.5 K capacity**
  - **Heat exchanger sizes**
  - **Over-the-road sizes**
  - **Experience**
- **Cryomodule piping pressure drops with 2+ km distances**
- **Cold compressor capacities**
- **With 192 modules, we reach our plant size limits, cold compressor limits, and pressure drop limits**
- **192 modules results in 2.47 km long cryogenic unit**
- **5 units (not all same length) per 250 GeV linac**
  - **Divides linac nicely for undulators at 150 GeV**

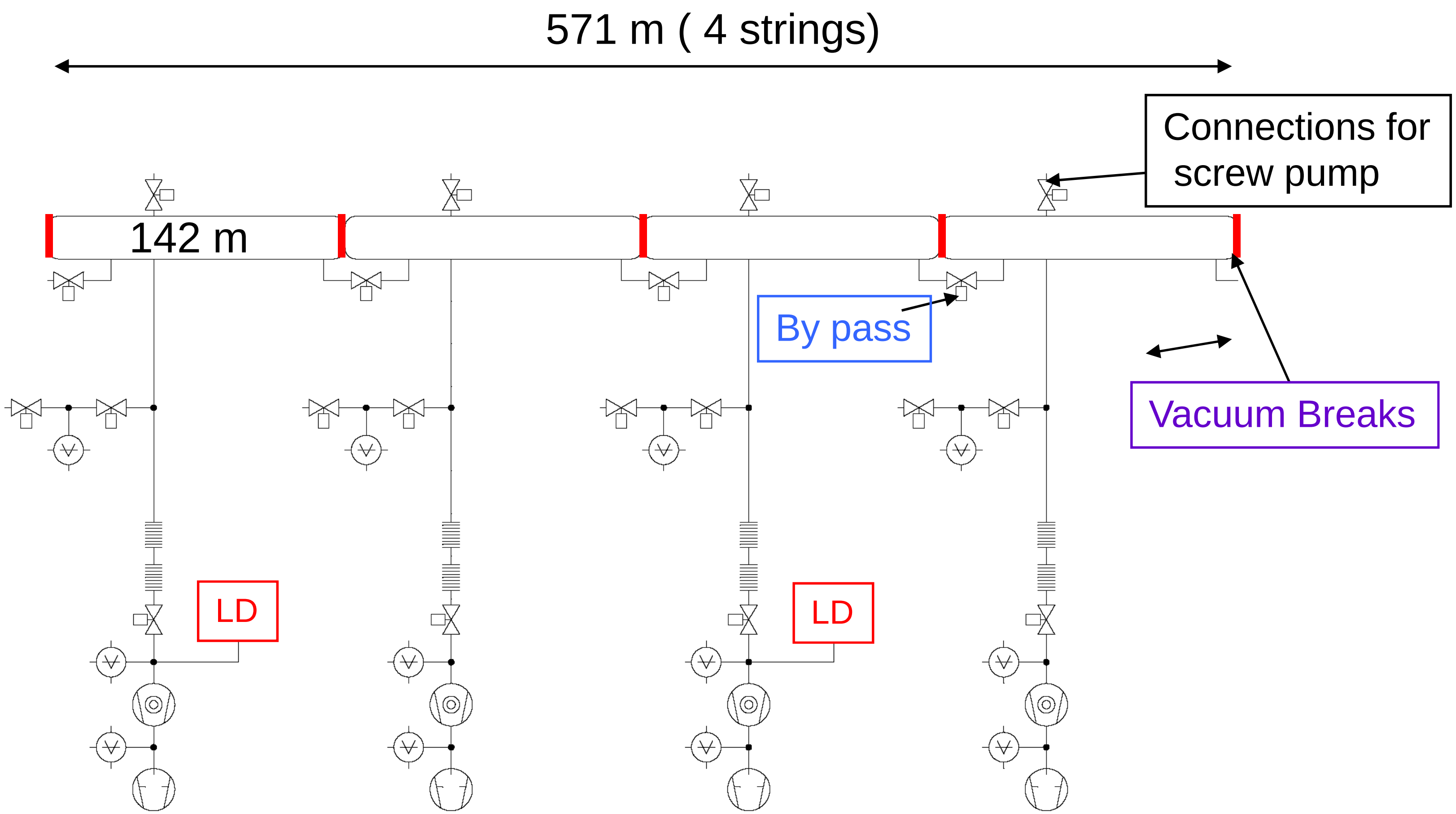
Beam line vacuum system



John Noonan, ANL
Yusuke Suetsugu,KEK
Paolo Michelato, INFN Milano

2 TMP pumping units with high sensitivity LD and RGA, safety, clean venting system, slow start pumping etc.

Insulating vacuum system



4 TMP pumping units: 2 with LD (leak detector) +
2 large screw pump for fore pumping

John Noonan, ANL
Yusuke Suetsugu,KEK
Paolo Michelato, INFN Milano

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 -- 2K

	TESLA		ILC 9-8-9		
	Static	Dynamic	Static	Dynamic	
Temperature Level	2K		2K		
RF load		4.95		7.46	Dynamic load scaled by the number of cavities and Gfac
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	1.70	1.68	
Static, dynamic sum	1.67	7.30	1.70	9.66	Total for 9-8-9 RF unit below
2K Sum [W]	9.0		11.4		34.08

Module predicted heat loads -- 5K

	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

Module predicted heat loads -- 40K

	TESLA		ILC 9-8-9		
	40K		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

		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	

CERN LHC capacity multipliers

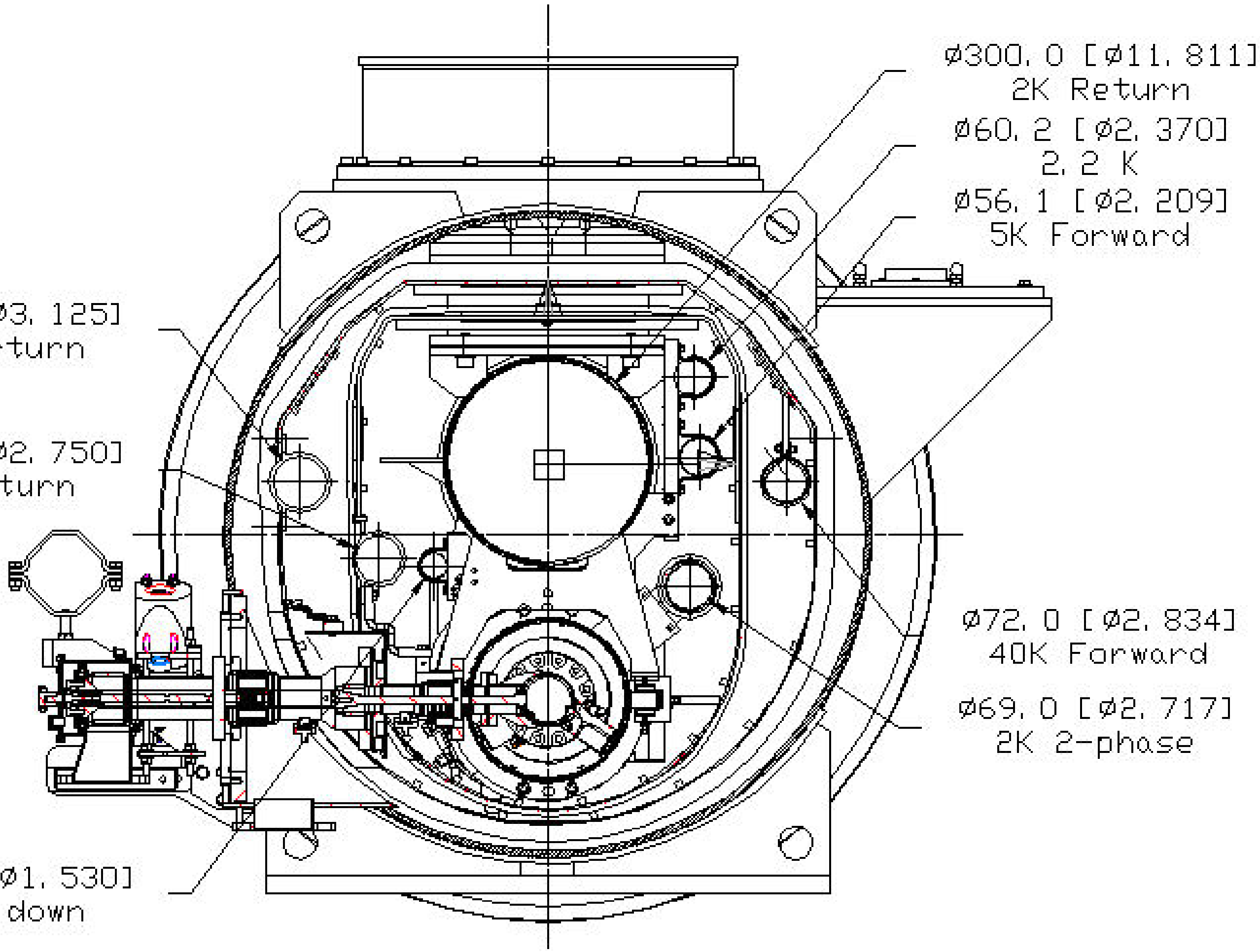
- We have adopted a modified version of the LHC cryogenic capacity formulation for ILC
- Cryo capacity = Fo x (Qd x Fud + Qs x Fus)
  - **Fo is overcapacity for control and off-design or off-optimum operation**
  - **Qs is predicted static heat load**
  - **Fus is uncertainty factor static heat load estimate**
  - **Fud is uncertainty factor dynamic heat load estimate**
  - **Qd is predicted dynamic heat load**

300 mm 2 K vapor tube (B)

Pressure drop in pipe (Pa) =	225.0
Pressure drop in pipe (mbar) =	**2.25**
Temperature rise due to pressure drop (K) =	**0.0245**

- Goal is no more than 3.0 mbar delta-P
- 300 mm ID tube pressure drop is 2.25 mbar (at 30 mbar)
  - **2.5 km**
  - **Assumed worst case flow, maximum plant output including all factors (0.93 gr/sec per module)**
  - **Pressure drop at about the limit. With much higher heat loads we would want shorter cryogenic units.**
  - **(my calculations, also in agreement with others)**

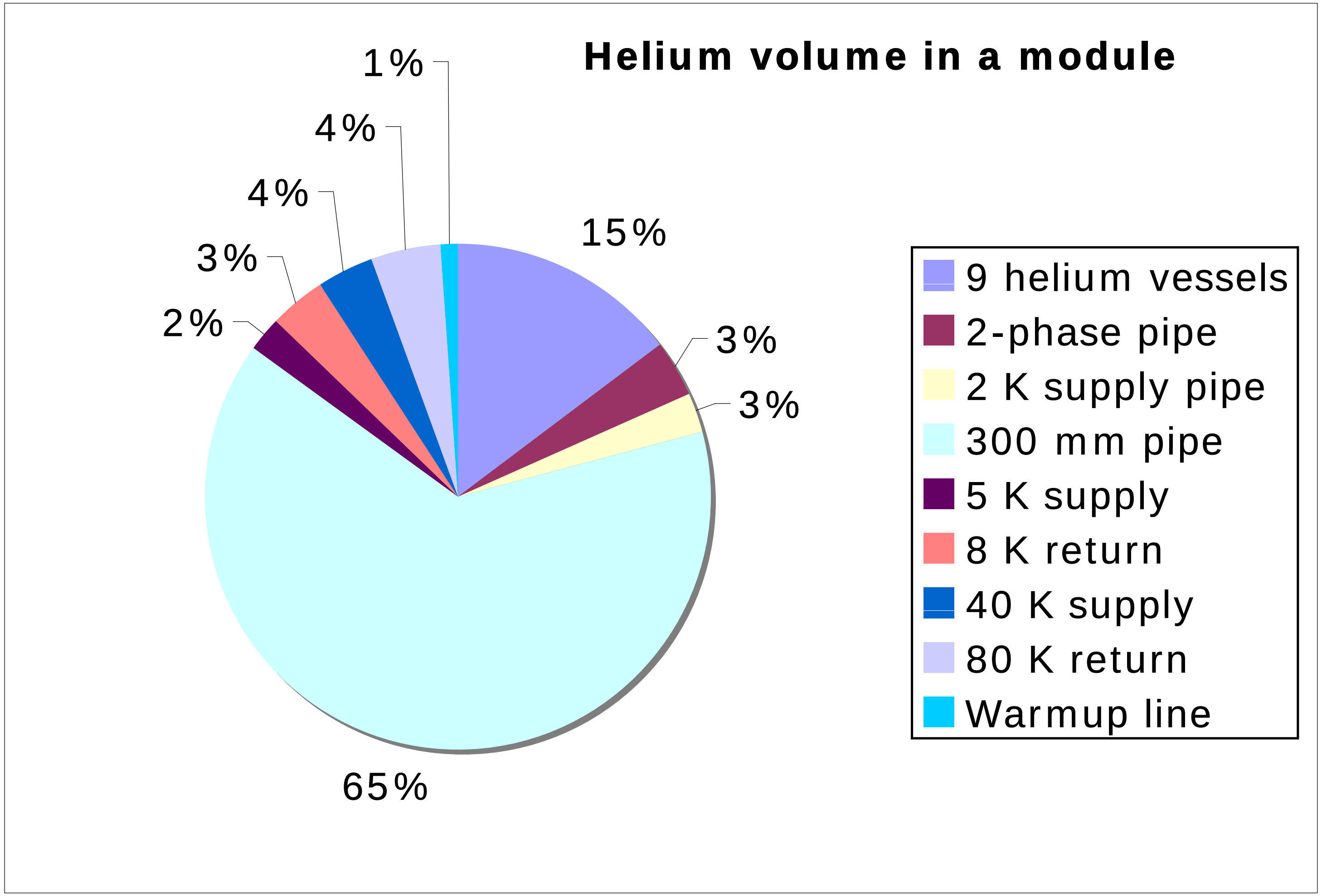
Type 4 cryomodule pipe sizes



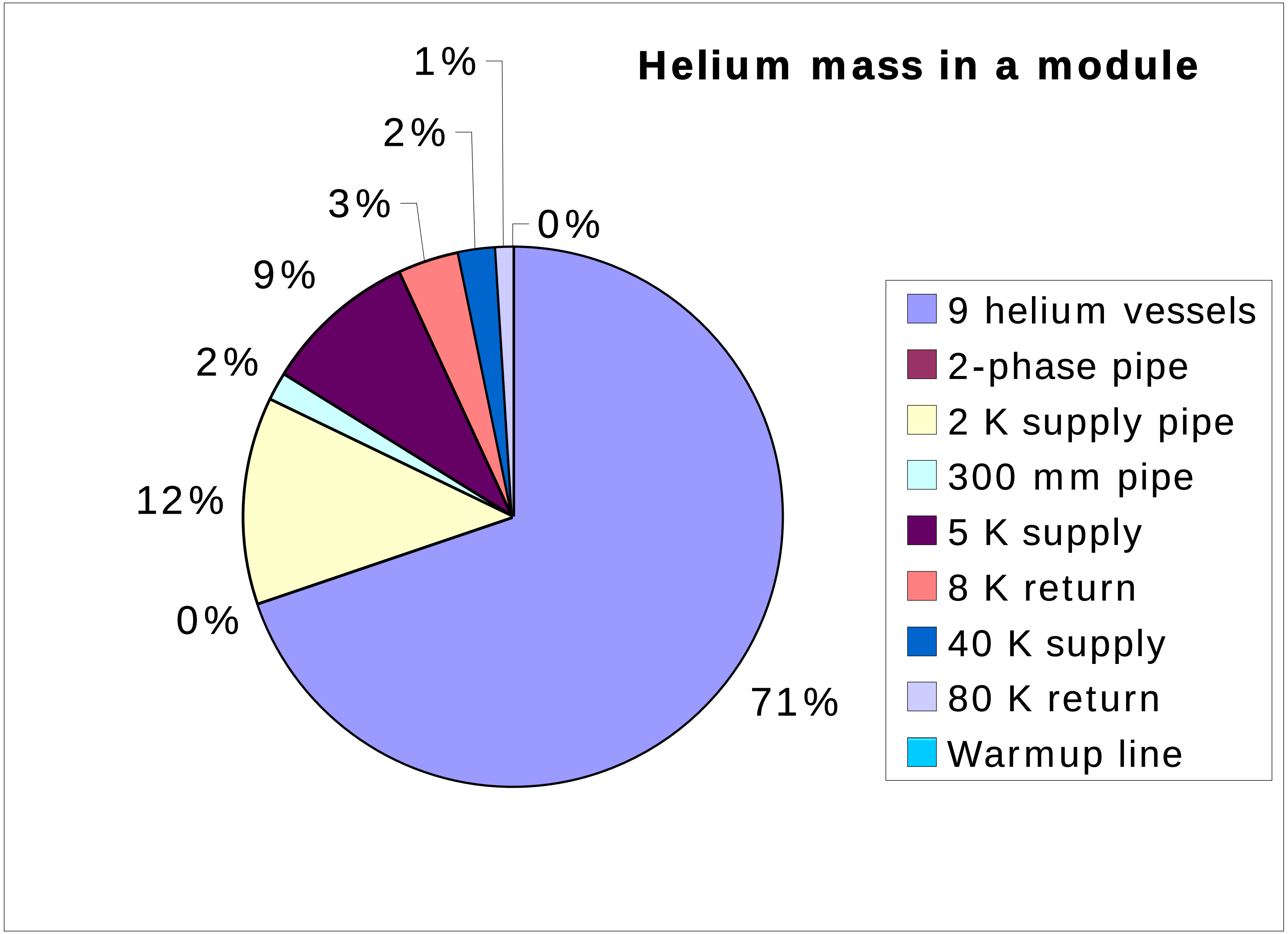
Pipe size summary now (July 07)

Pipe function	BCD name	TTF inner diameter (mm)	XFEL plan inner diameter (mm)	**ILC and T4CM proposed inner dia (mm)**	ILC allowed pressure drop
2.2 K subcooled supply	A	45.2	45.2	**60**	0.10 bar
Major return header, structural supp’t	B	300	300	**300**	3.0 mbar
5 K shield and intercept supply	C	54	54	**56.1**	
8 K shield and intercept return	D	50	65	**70**	0.20 bar (C+D)
40 – 80 K shield and intercept supply	E	54	65	**72**	
40 - 80 K shield and intercept return	F	50	65	**80**	1.0 bar (E+F)
2-phase pipe		72.1	>72.1	**72.1**	
Helium vessel to 2-phase pipe cross-connect		54.9	54.9	**54.9**	

Helium Volume in a Cryomodule



Helium Inventory in a Cryomodule



Off-design operation

- Helium venting with loss of vacuum
  - **Cryostat insulating vacuum (~6 W/cm^2)**
  - **Cavity vacuum (~2-4 W/cm^2)**
  - **Large flow rates**
  - **300 mm header acts as buffer**
  - **No venting to tunnel**
- Warm-up and cool-down
  - **Relatively low mass compared to magnet systems**
  - **Allow for greater mass of magnet package**

Maximum allowable pressures

- Helium vessel, 2 phase pipe, 300 mm header
  - **2 bar warm**
    - Limited by cavity detuning
    - Issue for pushing warm-up and cool-down flows
  - **4 bar cold**
    - Limited by cavity detuning
    - Issue for emergency venting
- Shield pipes
  - **20 bar**
    - Need high pressure for density to reduce flow velocities and pressure drops

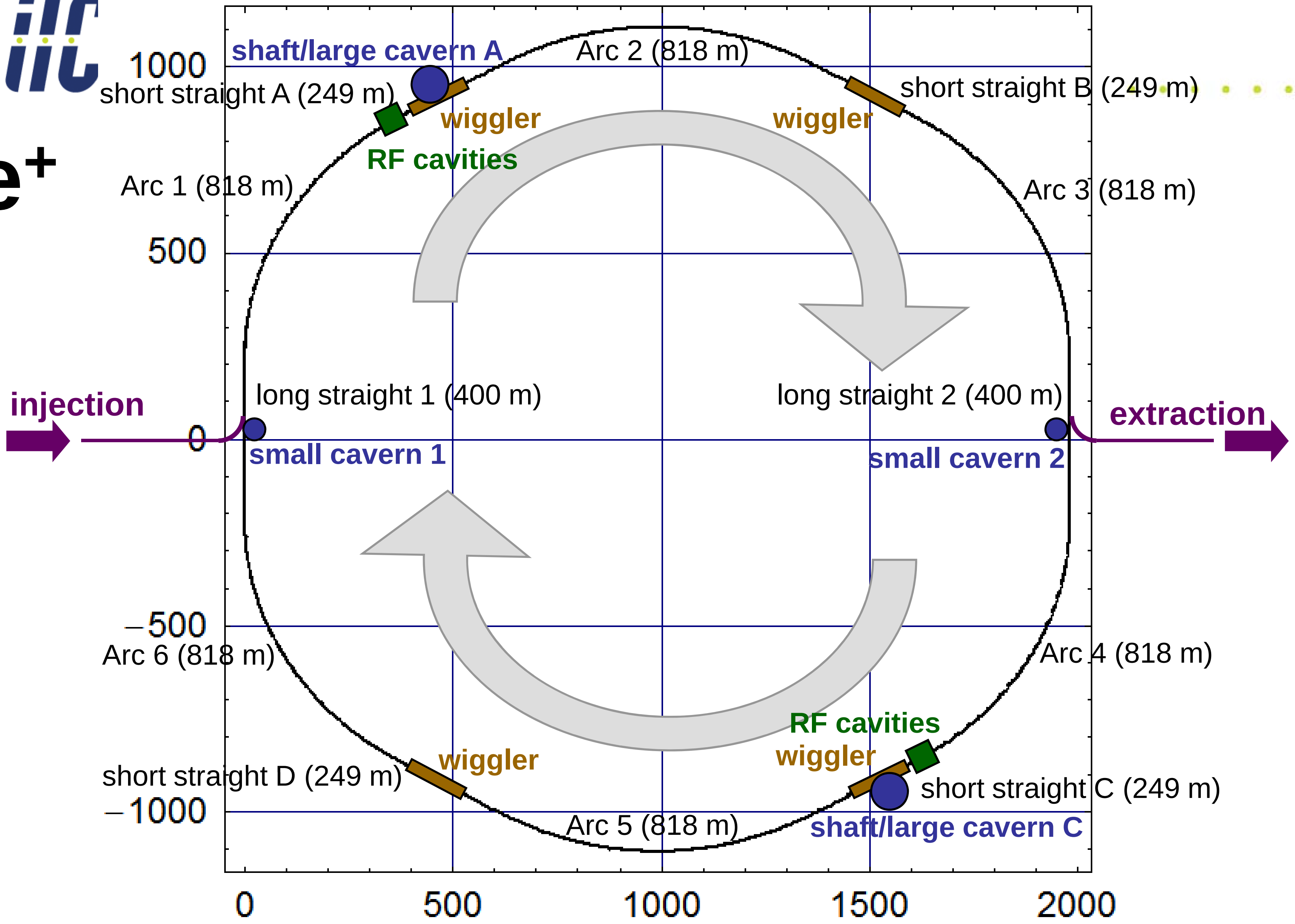
Main linac dominates ILC cryogenics but there is more . . . .

- The main linac cryoplants and associated equipment make up about 60% of total ILC cryogenic system costs
- Main linac distribution is another 20% of total ILC cryogenic system costs
  - **About half of that is 132 string connecting boxes**
- Total is about 80% of ILC cryogenic system costs attributable to the main linac

Source cryogenics

- Electron source
  - **25 modules, assembled as two strings**
  - **SC spin rotator section, 50 m long**
- Positron source
  - **22 modules, about half special with extra magnets, assembled as two strings**
  - **Undulator cryo in Main Linac**
  - **Overall module heat taken as same load as electron side**
- Costed as separate cryoplants, but may at least share compressors with pts 2 and 3.

e+


shaft/large cavern A
Arc 2 (818 m)
1000
short straight A (249 m)
short straight B (249 m)
wiggler
wiggler
RF cavities
Arc 1 (818 m)
Arc 3 (818 m)
500
injection
long straight 1 (400 m)
long straight 2 (400 m)
extraction
0
small cavern 1
small cavern 2
−500
Arc 6 (818 m)
Arc 4 (818 m)
RF cavities
wiggler
wiggler
short straight D (249 m)
short straight C (249 m)
−1000
Arc 5 (818 m)
shaft/large cavern C
0
500
1000
1500
2000

Damping ring cryogenics

	e- RF module	e+ RF module	e- wiggler	e+ wiggler
	(one cavity per module)		(2.5 meters)	(2.5 meters)
Static 4.5 K heat per module or magnet (W)	30.0	30.0	5.0	5.0
Dynamic 4.5 K heat per module or magnet (W)	40.0	40.0	0.0	0.0
4.5 K liquid per pair wiggler current leads (g/s)			0.01	0.01
Number of modules or magnets per string	9	9	20	20
Total 4.5 K heat per string (W)	630.0	630.0	100.0	100.0
Total 4.5 K liquid per string (g/s)			0.2	0.2
Number of strings per ring	2	2	4	4
Number of modules or magnets per ring	18.0	18.0	80.0	80.0
Number of strings per cryoplant	1	1	2	2
Total 4.5 K heat per cryoplant (W)	630.0	630.0	200.0	200.0
Total 4.5 K liquid per cryoplant (g/s)			0.4	0.4
Static 70 K heat (W)	50.0	50.0	50.0	50.0
Dynamic 70 K heat (W)	10.0	10.0	0.0	0.0
Number per string	9	9	20	20
Total 70 K heat per string (W)	540.0	540.0	1000.0	1000.0
Number of strings per cryoplant	1	1	2	2
Total 70 K heat per cryoplant (W)	540.0	540.0	2000.0	2000.0

Notes: 2 cryoplants total for damping rings

- Result is two cryoplants each of total capacity equivalent to 3.5 kW at 4.5 K.

Beam delivery system cryogenics

- Crab cavities (3.9 GHz) at 1.8 K plus magnets
  - **Not including detector cooling nor moveable magnets**
- 80 W at 1.8 K ==> 4 gr/sec liquefaction plus room-temperature pumping
- In total for one 14 mr IR
  - **4 gr/sec at 4.5 K**
  - **400 W at 4.5 K**
  - **2000 W at 80 K**
- Overall capacity equivalent to about 1.9 kW at 4.5 K for one plant cooling both sides of one IR
  - **Similar in size and features to an RF test facility refrigerator**

ILC cryogenic system inventory

Volumes		Helium (liquid liters equivalent)	Tevatron equivalents	LHC equivalents	Inventory cost (K$)
One module		346.1			
String	12 modules	4,153.3	0.1		12.46
Cryogenic unit	14-16 strings	62,991.5	1.0	0.1	188.97
ILC main linacs	2x5 cryo units	630,260.9	10.5	0.8	1890.78

Since we have not counted all the cryogenic subsystems and storage yet, ILC probably ends up with a bit more inventory than LHC

ILC cryogenic plant size summary

Area	Number of plants	Installed plant size (each) (MW)	Installed total power (MW)	Operating power (each) (MW)	Operating total power (MW)
Main Linac + RTML	10.00	4.28	42.80	3.34	33.40
Sources	2.00	0.59	1.18	0.46	0.92
Damping Rings	2.00	1.13	2.26	0.88	1.76
BDS	1.00	0.41	0.41	0.33	0.33
TOTAL			**46.65**		**36.41**

- TESLA 500 TDR for comparison
  - **5 plants at ~5.15 MW installed**
  - **2 plants at ~3.5 MW installed**
  - **Total 32.8 MW installed**
  - **Plus some additional for damping rings**

Cryoplants compared to TESLA

- Why more cryo power in ILC than TESLA?
  - **Dynamic load up with gradient squared (linac length reduced by gradient)**
  - **Lower assumptions about plant efficiency, in accordance with recent industrial estimate, see table below**

Cryoplant coefficient of performance (W/W)

	40 K - 80 K	5 K - 8 K	2 K
TESLA TDR:	17	168	588
XFEL:	20	220	870
Industrial est:	16.5	200	700
ILC assumption:	16.4	197.9	703.0

Cryogenic system design status

- Fairly complete accounting of cold devices with heat load estimates and locations
  - **Focus has been on main linac cryomodules**
  - **Some other cold devices still not well defined**
  - **Some heat loads are very rough estimates**
- Cryogenic plant capacities have been estimated
  - **Overall margin about 1.54**
  - **Main linac plants dominate, each at 20 kW @ 4.5 K equivalent total capacity**
- Component conceptual designs (distribution boxes, end boxes, transfer lines) are still sketchy
  - **Need these to define space requirements and make cost estimates**
  - **Used area system lattice designs to develop transfer line lengths and conceptual cryosystem layouts**

ILC Engineering Design Phase

- A 2 - 3 year effort to create a more complete ILC design
  - **Starting now**
  - **Precise scope not yet defined**
  - **Work will be internationally distributed**
  - **ILC cryogenic system and cryomodule design are a major part of the engineering design phase effort**

Towards the EDR

- Contract with industry for main linac cryogenic plant conceptual designs and cost studies
  - **Need to integrate plant cycle with cryomodule conditions**
  - **Will feed back to system design and cryomodule design**
- Continue to refine heat load estimates and required plant sizes
- Refine system layout schemes to optimize plant locations and transfer line distances
  - **Particularly for the sources, damping rings, and beam delivery system**
  - **Develop cryogenic process, flow, and instrumentation diagrams and conceptual equipment layouts**
- Develop more detailed conceptual designs for the various end boxes, distribution boxes, and transfer lines
- Refine liquid control schemes so as to understand use of heaters and consequent heat loads (allowed for in Fo = 1.4)

Towards the EDR - 2

- Consider impact of cool-down, warm-up and off-design operations
- Evaluate requirements for loss-of-vacuum venting
- Conceptual designs for large 2 kelvin heat exchangers
  - **Not distributed as in LHC**
- Consider how to group surface components to reduce surface impact
- Compliance with engineering standards, particularly in cryogenic modules
- Damping ring cryogenic system
- Beam delivery cryogenic system

For more information

- http://www.linearcollider.org/
  - **The ILC home page**
  - **Includes a link to the full Reference Design Report (RDR)**
- http://tesla-new.desy.de/
  - **TESLA Technology Collaboration home page**
  - **Links to RF cavity database, publications and ~15 years of 1.3 GHz SRF documentation and experience, the basis for ILC technology**
- E-mail me at Tommy@fnal.gov