An Overview of the International Linear Collider (ILC) Cryogenic System

Tom Peterson, Fermilab

Cryogenic Operations Workshop at SLAC

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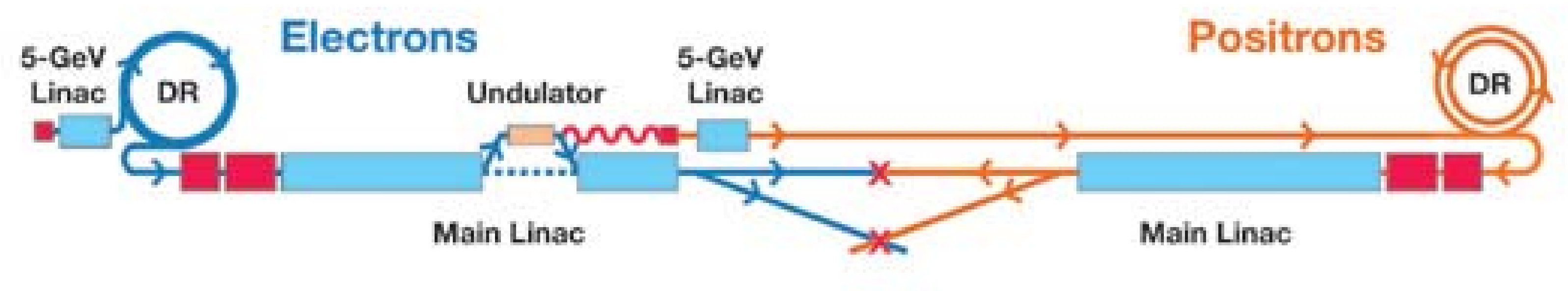
ILC cryogenic system effort is a very active collaboration

- CEA Grenoble, CERN, DESY, Fermilab, Jefferson Lab, KEK, SLAC
- The concepts presented today represent the work of many people at these laboratories
- Previous input from industry for the TESLA effort and for LHC is also important

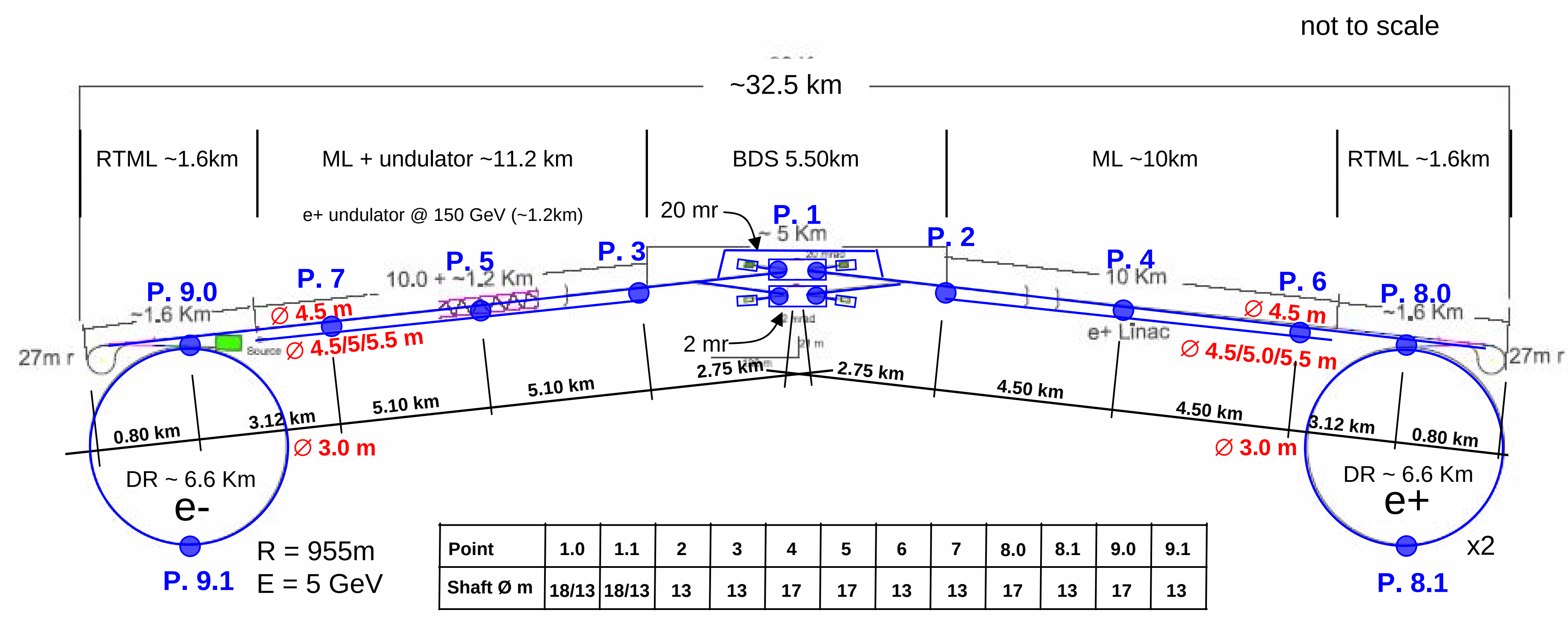
ILC schematic



- An electron-positron collider with two interaction regions
- 250 GeV x 250 GeV in first phase
- To follow and complement LHC experiments

SCHEMATIC LAYOUT (slide from CFS group)

ILC UNDERGROUND STRUCTURES (500 GeV)



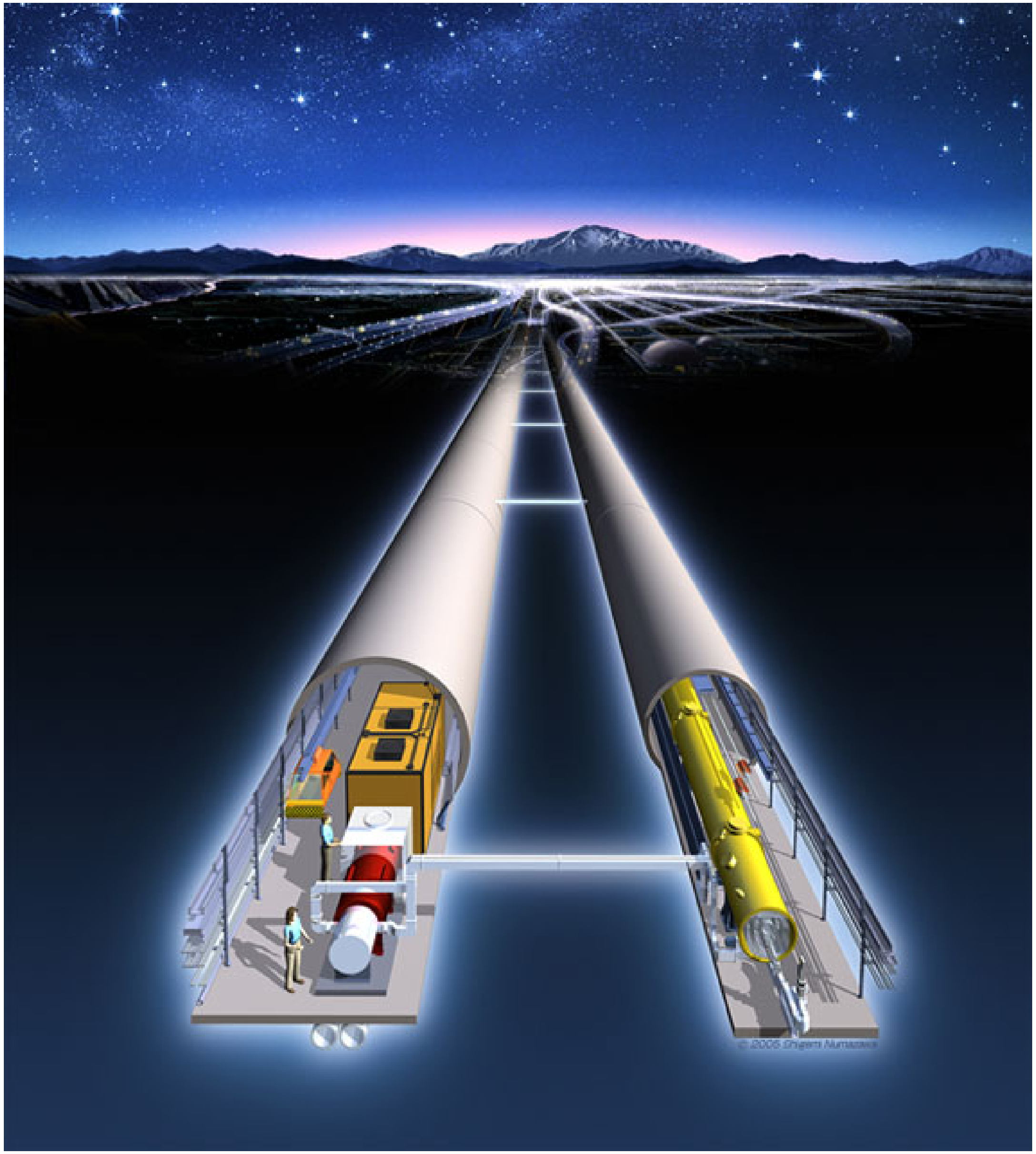
Point	1.0	1.1	2	3	4	5	6	7	8.0	8.1	9.0	9.1
Shaft Ø m	18/13	18/13	13	13	17	17	13	13	17	13	17	13

Among CFS Group duties :

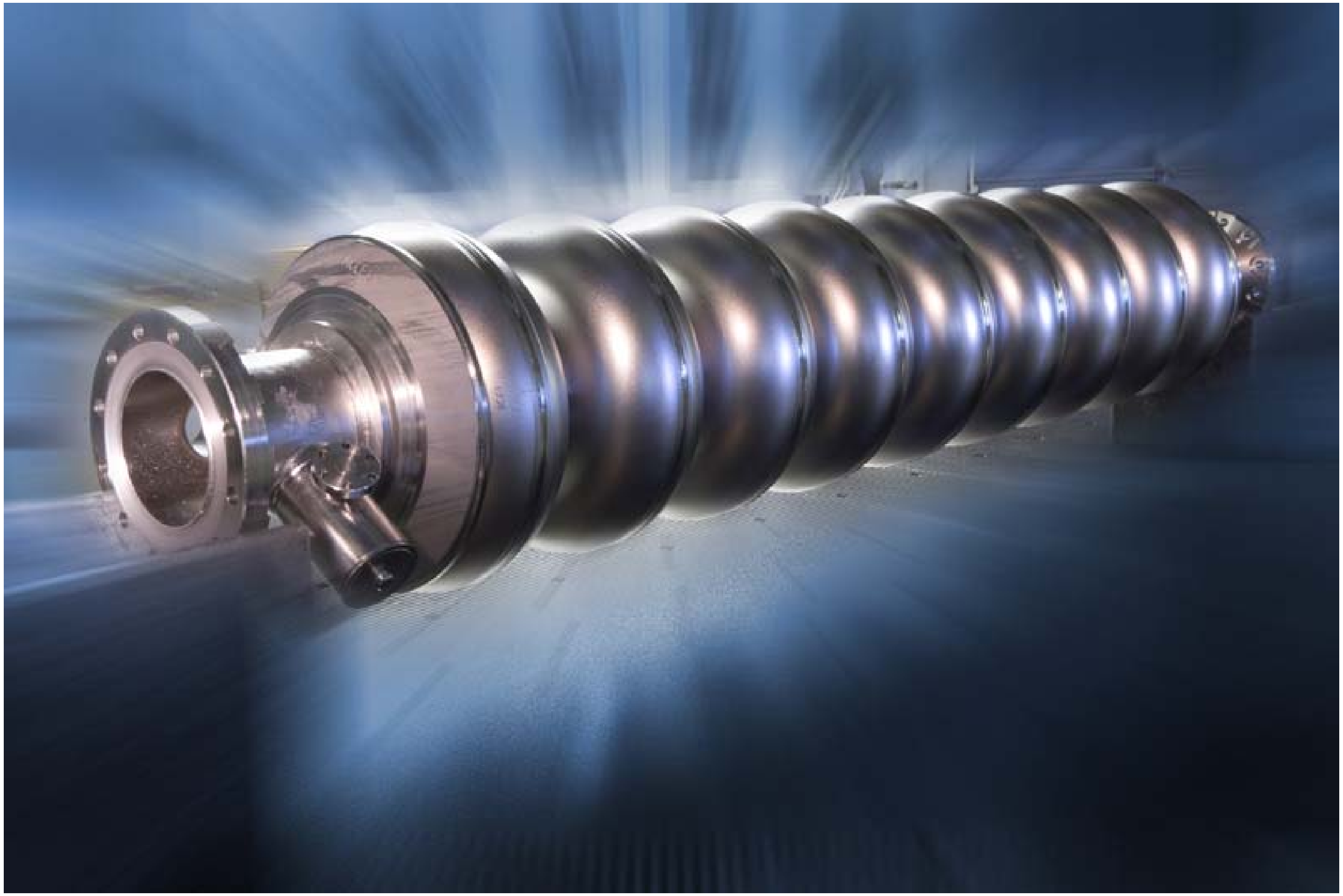
- ***Ask appropriate questions ASAP (avoid late surprises)***
- ***Keep the cost of the CFS within acceptable limit***

● **Shaft**

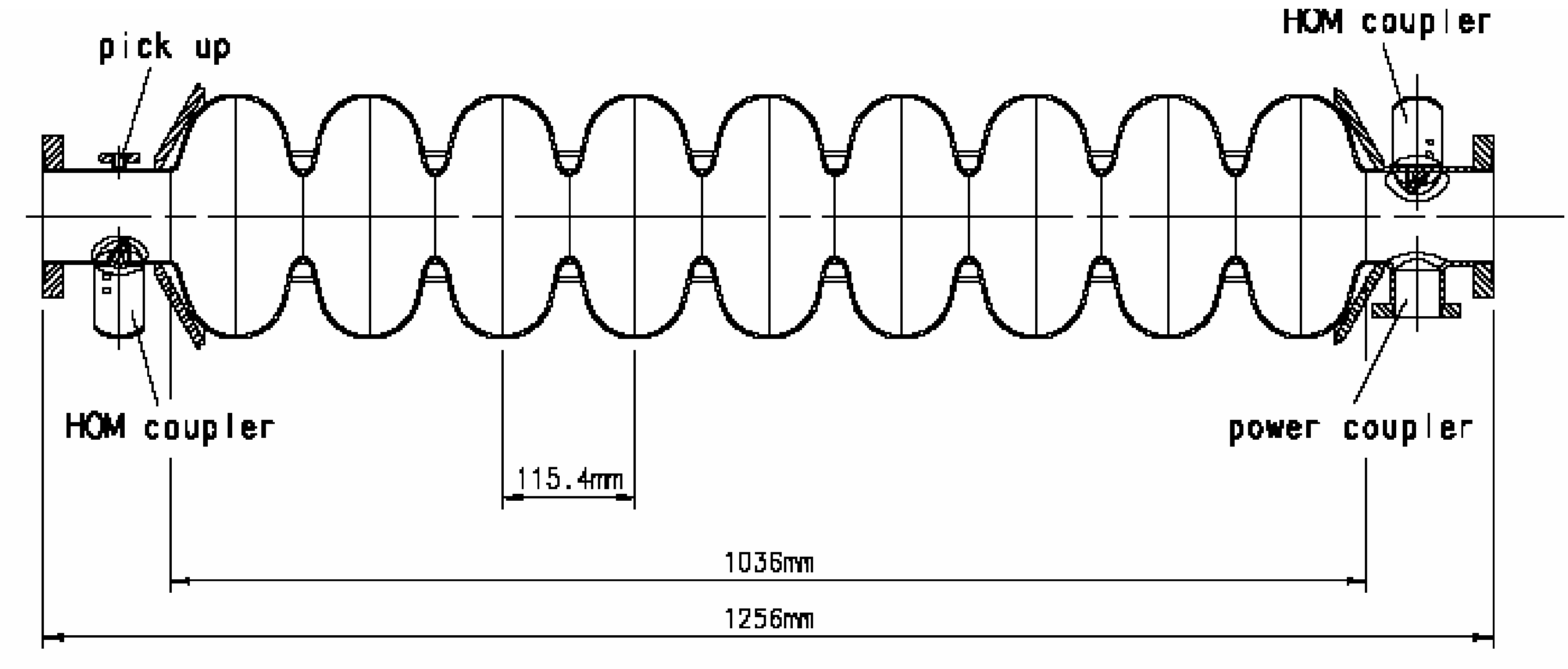
Artist's conception of ILC courtesy of KEK



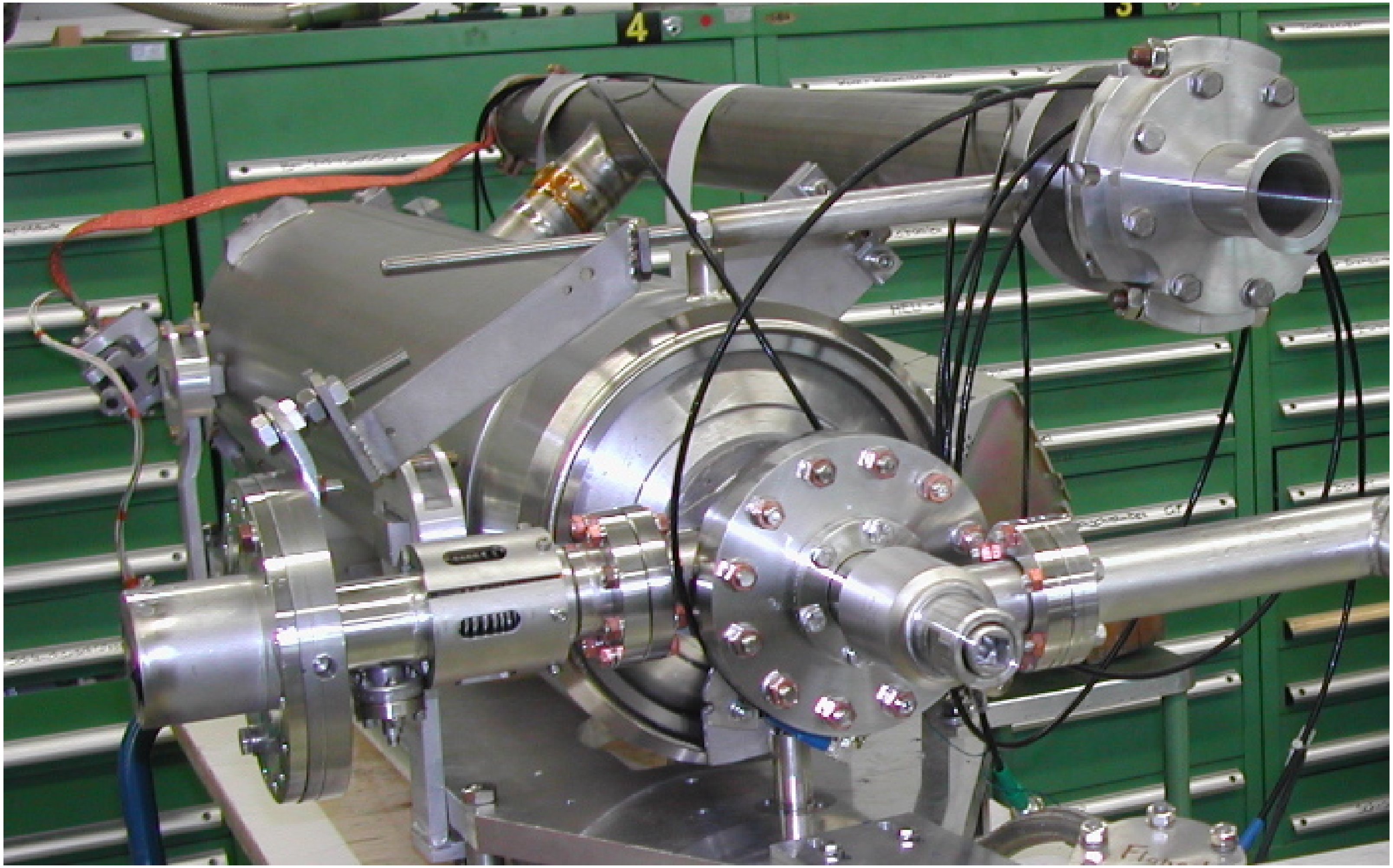
9-cell niobium RF cavity



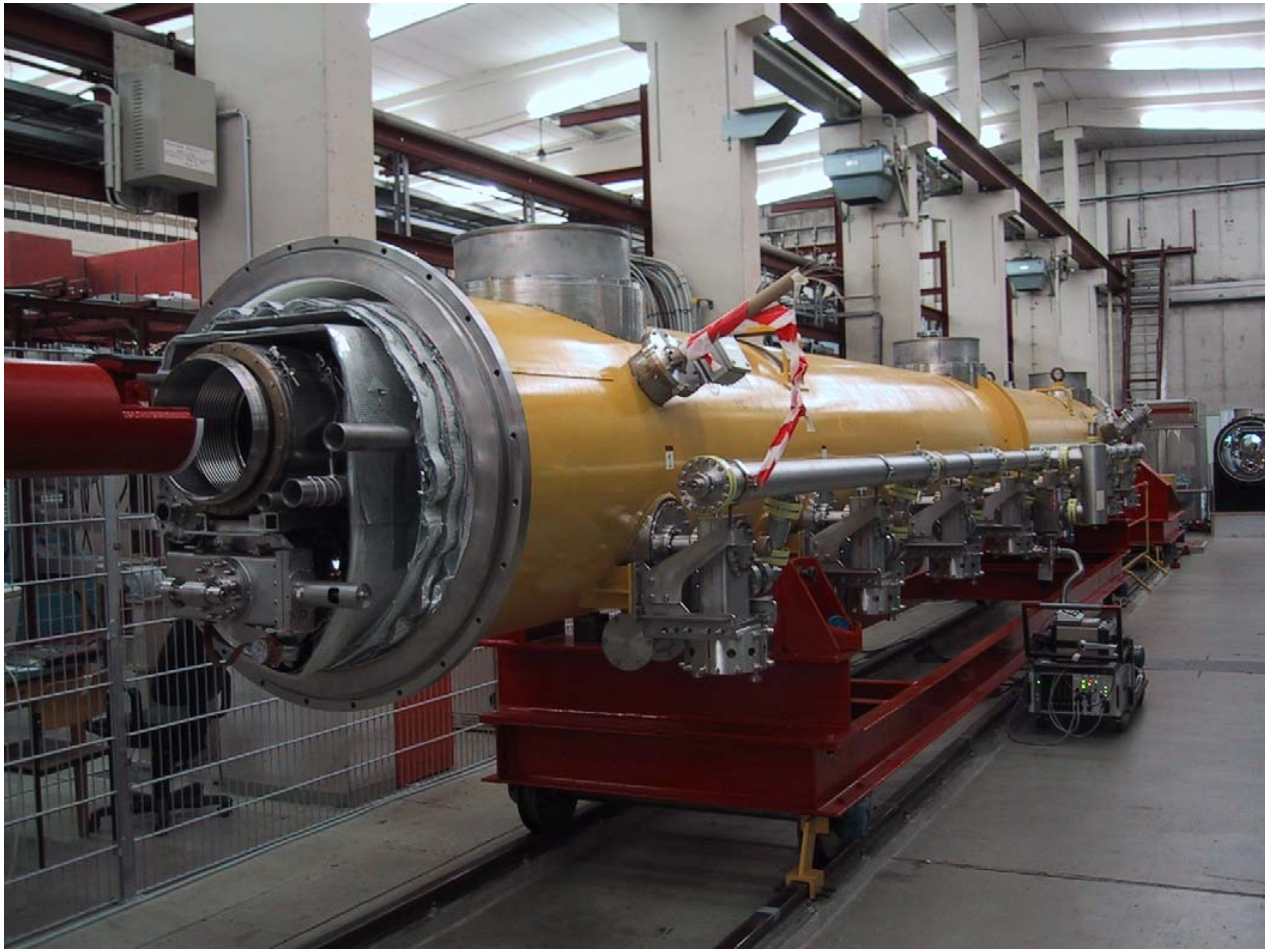
1.3 GHz, 9 cell, Nb RF Cavity



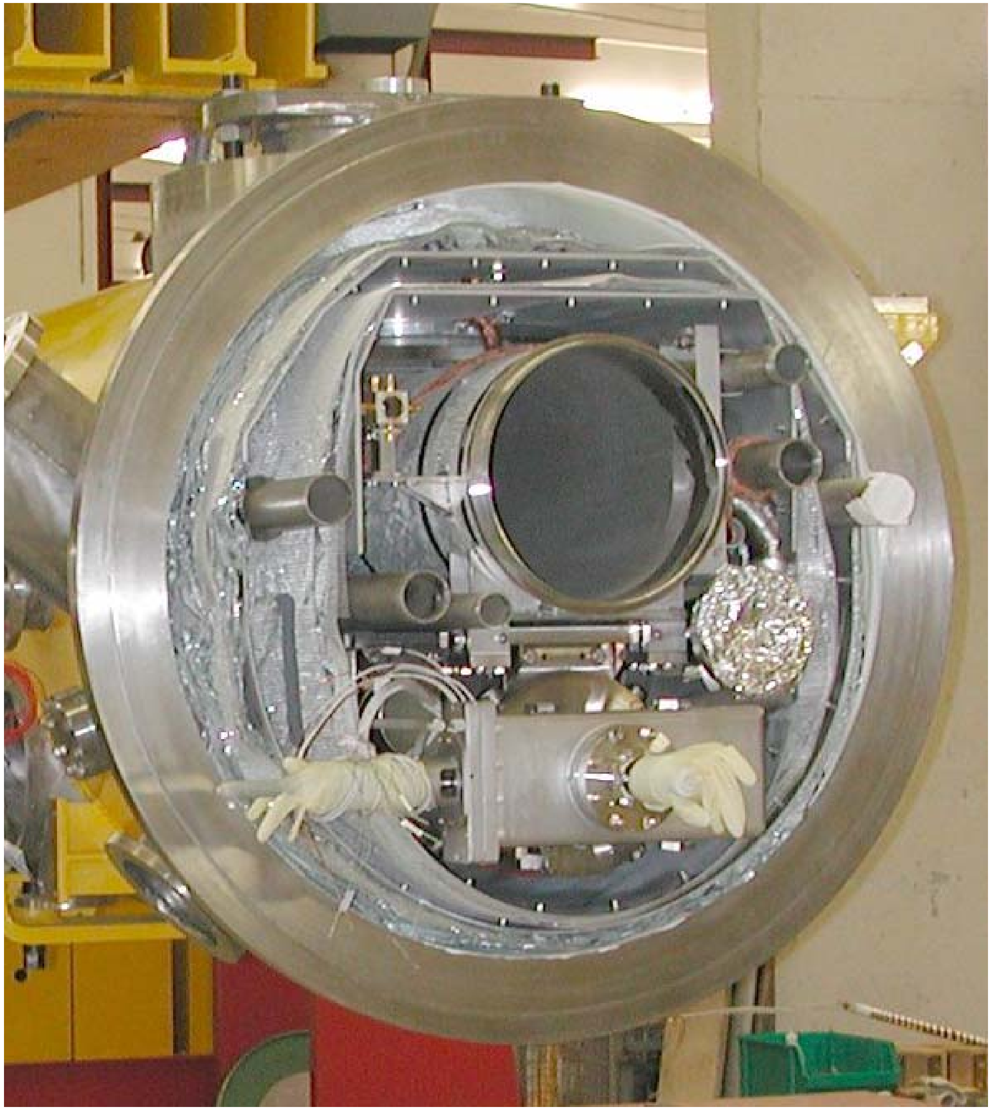
“Dressed” cavity



TTF cryomodule



Module end



ILC cryogenic system definition

- The cryogenic system is taken to include cryogen distribution as well as production
  - Cryogenic plants
  - Distribution and interface boxes
    - Including non-magnetic, non-RF cold tunnel components
  - Transfer lines
- Production test systems will also include significant cryogenics

ILC modules and cryogenic system are closely based on the TESLA Technical Design Report (TDR)

- TESLA TDR is available online (see references)
- 9-cell niobium RF cavities at 1.3 GHz and 2 Kelvin are the primary accelerating structures
- Cavities are assembled into a cryostat called a “cryomodule” or “module”
- ILC module concept is still the TDR module, except 8 cavities instead of 12 per module
- TDR cryogenic system concept is retained

ILC cryogenic system overview (main linac)

- Revising and resizing the TESLA cryogenic concept
- Saturated He II cooled cavities @ 2 K
- Helium gas thermal shield @ 5 - 8 K
- Helium gas thermal shield @ 40 - 80 K
- Two-phase line (liquid helium supply and concurrent vapor return) connects to each helium vessel
- Two-phase line connects to gas return once per module
- A small diameter warm-up/cool-down line connects the bottoms of the He vessels (primarily for warm-up)
- Subcooled helium supply line connects to two-phase line via JT valve once per “string” (12 modules)

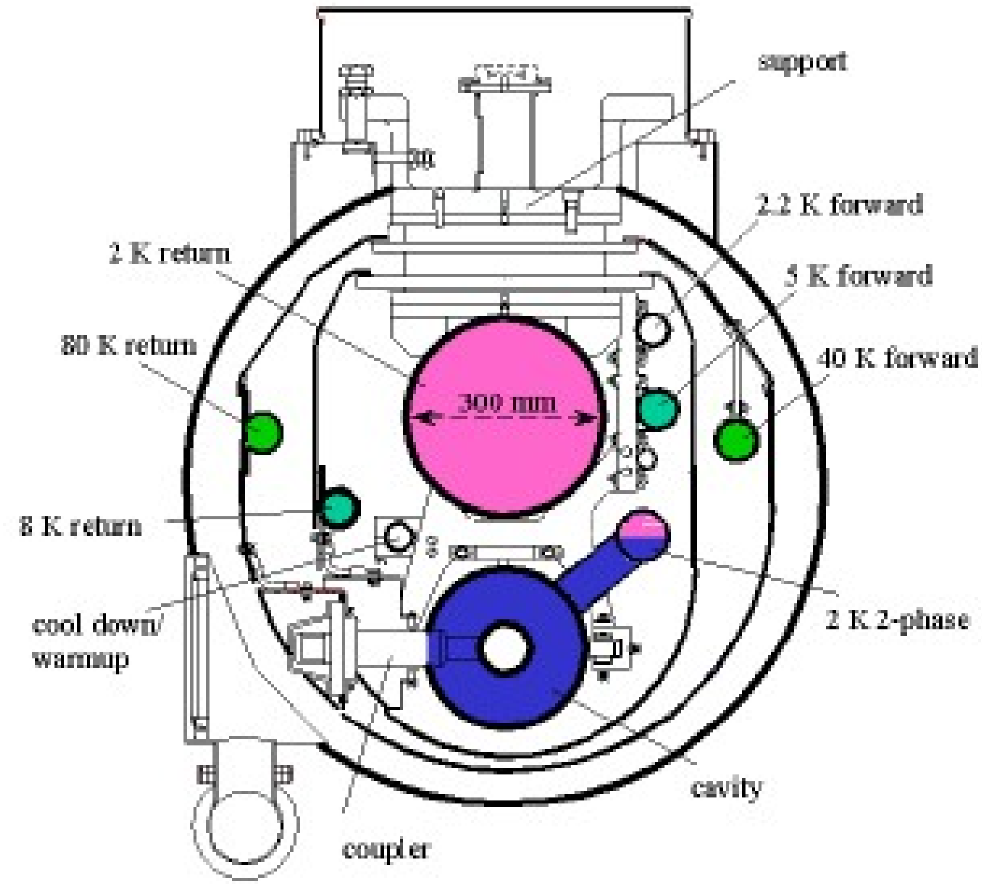


Figure 3.2.11: *Cross section of cryomodule.*

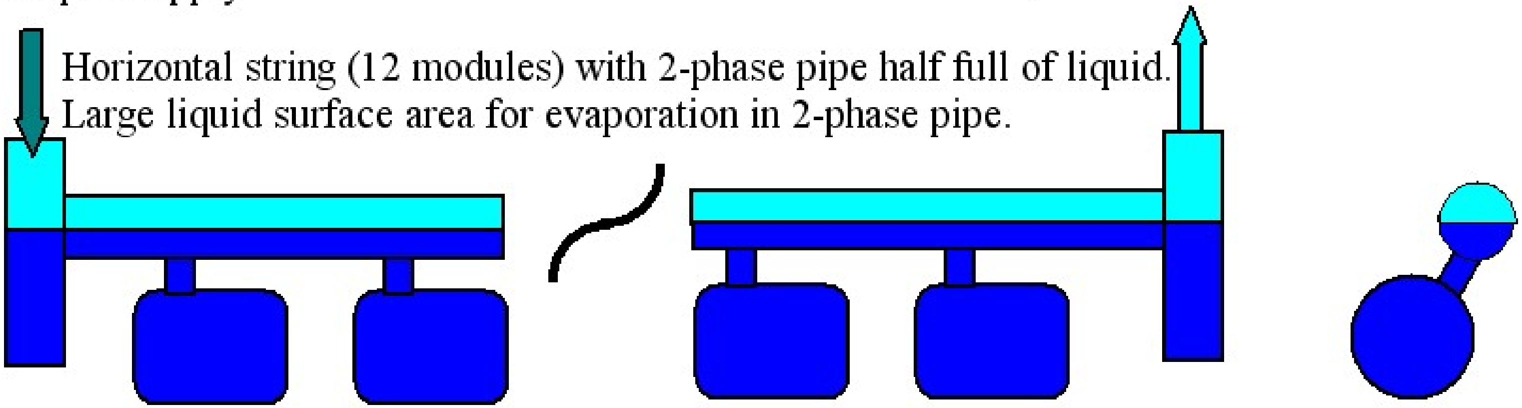
ILC

Helium vessel liquid management

Liquid supply

Vapor return

Horizontal string (12 modules) with 2-phase pipe half full of liquid.
Large liquid surface area for evaporation in 2-phase pipe.

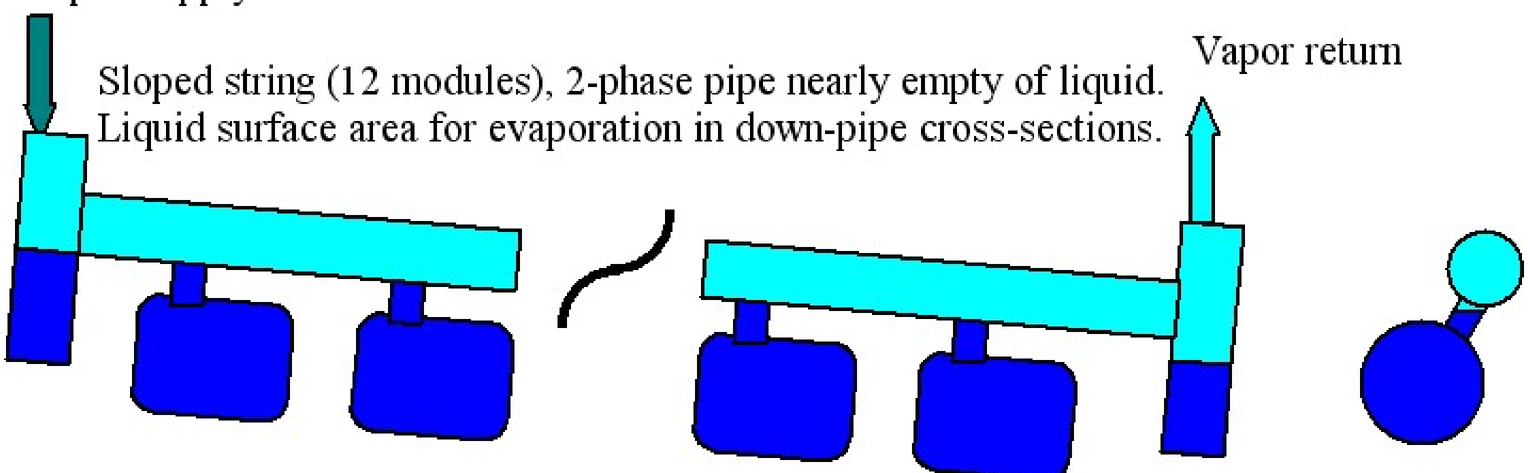


This is the way that TTF has been running, with liquid partially filling the 2-phase pipe.

Liquid supply

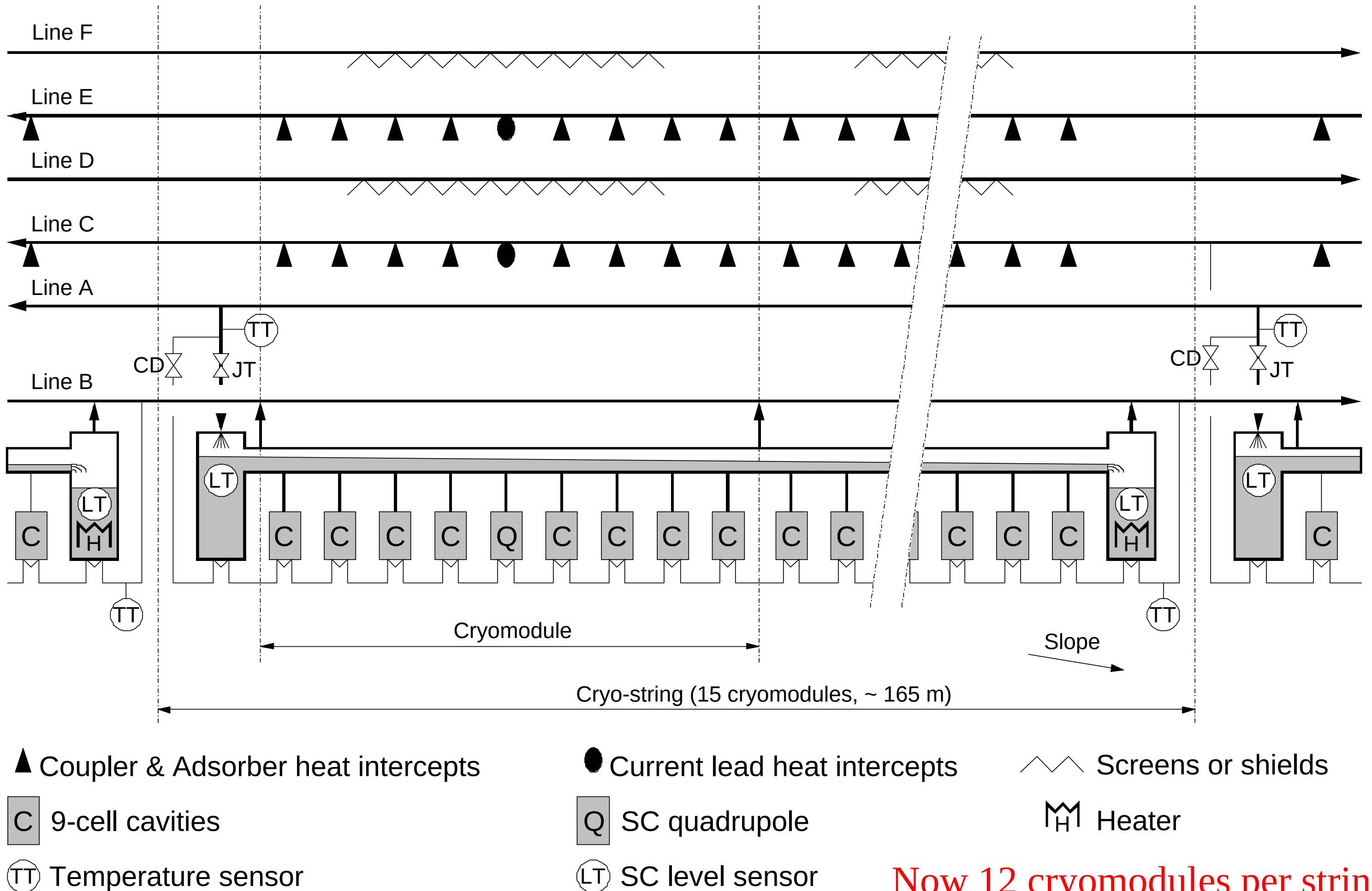
Vapor return

Sloped string (12 modules), 2-phase pipe nearly empty of liquid.
Liquid surface area for evaporation in down-pipe cross-sections.



This is the way that a sloped ILC (and XFEL) would operate, with liquid running down the 2-phase pipe, filling each helium vessel, and excess liquid dropping into a vessel at the string end where it is boiled away by a small electric heater.

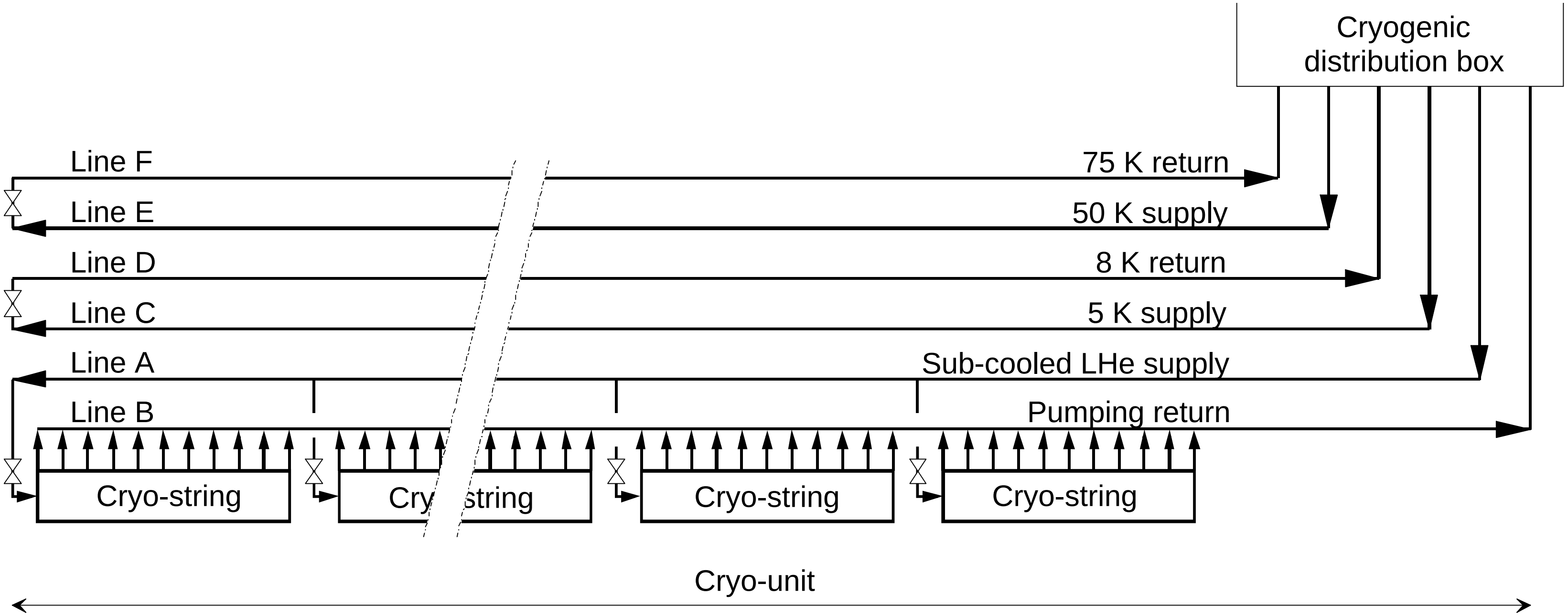
Cryo-string



Now 12 cryomodules per string, totalling 140 m

Cryogenic unit

16 strings per cryogenic unit, so 192 modules per cryo unit (47 GeV)



Module predicted heat loads

	Heat loads at 40 K – 80 K level (W/module)	Heat loads at 5 K - 8 K level (W/module)	Heat loads at 2 K level (W/module)
TTF typical measured static	74.0	13.0	3.5
Dynamic predicted at 31.5 MV/m, Q0 = 1E10, 5 Hz	105.25	4.87	8.37
Total predicted at **31.5** MV/m, Q0 = 1E10, 5 Hz	**179.25**	**17.87**	**11.87**
Dynamic predicted at 36.0 MV/m, Q0 = 1E10, 5 Hz	127.22	5.31	10.25
Total predicted at **36.0** MV/m, Q0 = 1E10, 5 Hz	**201.22**	**18.31**	**13.75**
TESLA 500 TDR total scaled to 8 cavity module for comparison	***122.0***	***10.6***	***6.0***

Cryogenic unit parameters

		40 K to 80 K	5 K to 8 K	2 K	
Predicted module static heat load	(W/module)	74.00	13.00	3.50	
Predicted module dynamic heat load	(W/module)	105.25	4.87	8.37	
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)	35.42	3.63	2.48	
Heat uncertainty factor (on static only)		1.50	1.50	1.50	
Design heat load per cryogenic unit	(kW)	43.02	4.98	2.92	
Design mass flow per cryogenic unit	(g/s)	206.15	155.35	141.12	
Design ideal power	(kW)	198.11	236.53	450.83	
Efficiency (fraction Carnot)		0.30	0.30	0.20	
Efficiency in Watts/Watt	(W/W)	15.35	158.35	773.28	
Nominal operating power	(kW)	660.36	788.44	2254.15	
					Overall
Overcapacity factor		1.40	1.40	1.40	multiplier
Overall net cryogenic capacity multiplier		1.70	1.92	1.65	1.71
Installed power	(kW)	924.50	1103.81	3155.81	
Installed 4.5 K equiv	(kW)	4.22	5.04	14.42	
Installed 4.5 K equiv per unit length	(W/m)	1.86	2.22	6.34	
Percent of total power at each level		0.18	0.21	0.61	

Total operating power for one cryo unit (MW)	3.70
Total installed power for one cryo unit (MW)	5.18
Total installed 4.5 K equivalent power for one cryo unit (kW)	23.69
Fraction of largest practical cryoplant per cryogenic unit	0.95

CERN LHC capacity multipliers

- Cryo capacity = Fo x (Qd + Qs x Fu)
  - Fo is overcapacity for control and off-design or off-optimum operation
  - Fu is uncertanty factor on load estimates, taken on static heat loads only
  - Qd is predicted dynamic heat load
  - Qs is predicted static heat load

Heat Load evolution in LHC

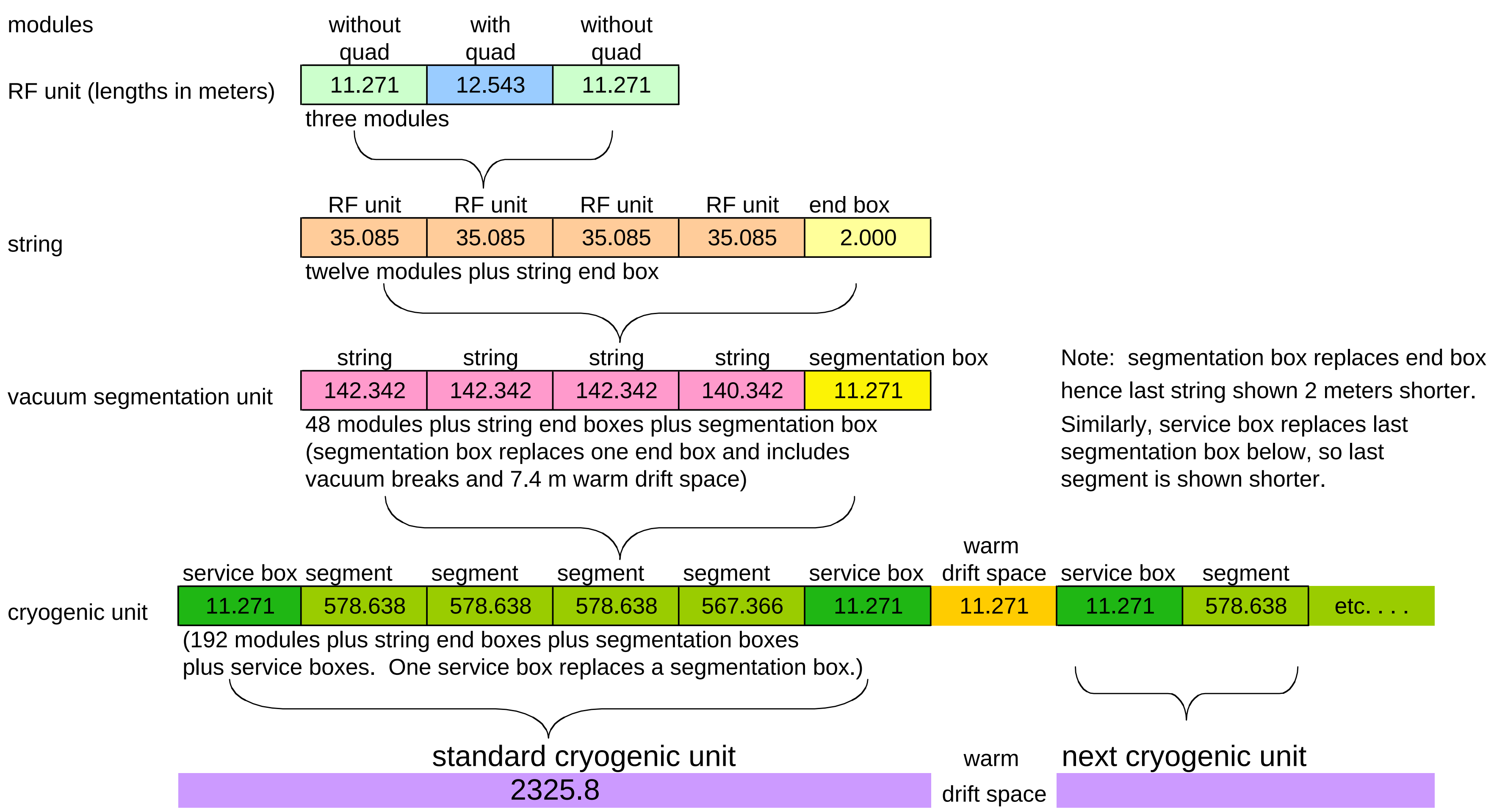
Basic Configuration: Pink Book 1996
Design Report: Design Report Document 2004

Temperature level	Heat load increase w/r to Pink Book	Main contribution to the increase
50-75 K	1,3	Separate distribution line
4-20 K	1,3	Electron-cloud deposition
1,9 K	1,5	Beam gas scattering, secondaries, beam losses
Current lead cooling	1,7	Separate electrical feeding of MB, MQF & MQD

At the early design phase of a project, margins are needed to cover unknown data or project configuration change.

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 2.33 km long cryogenic unit -- 5 units per 250 GeV linac
  - Divides linac nicely for undulators at 150 GeV


modules
without quad
with quad
without quad
RF unit (lengths in meters)
11.271
12.543
11.271
three modules
string
RF unit
RF unit
RF unit
RF unit
end box
35.085
35.085
35.085
35.085
2.000
twelve modules plus string end box
vacuum segmentation unit
string
string
string
string
segmentation box
142.342
142.342
142.342
140.342
11.271
48 modules plus string end boxes plus segmentation box (segmentation box replaces one end box and includes vacuum breaks and 7.4 m warm drift space)
Note: segmentation box replaces end box hence last string shown 2 meters shorter.
Similarly, service box replaces last segmentation box below, so last segment is shown shorter.
cryogenic unit
service box
segment
segment
segment
segment
service box
warm drift space
service box
segment
11.271
578.638
578.638
578.638
567.366
11.271
11.271
11.271
578.638
etc. . . .
(192 modules plus string end boxes plus segmentation boxes plus service boxes. One service box replaces a segmentation box.)
standard cryogenic unit
2325.8
warm drift space
next cryogenic unit

Some operational issues

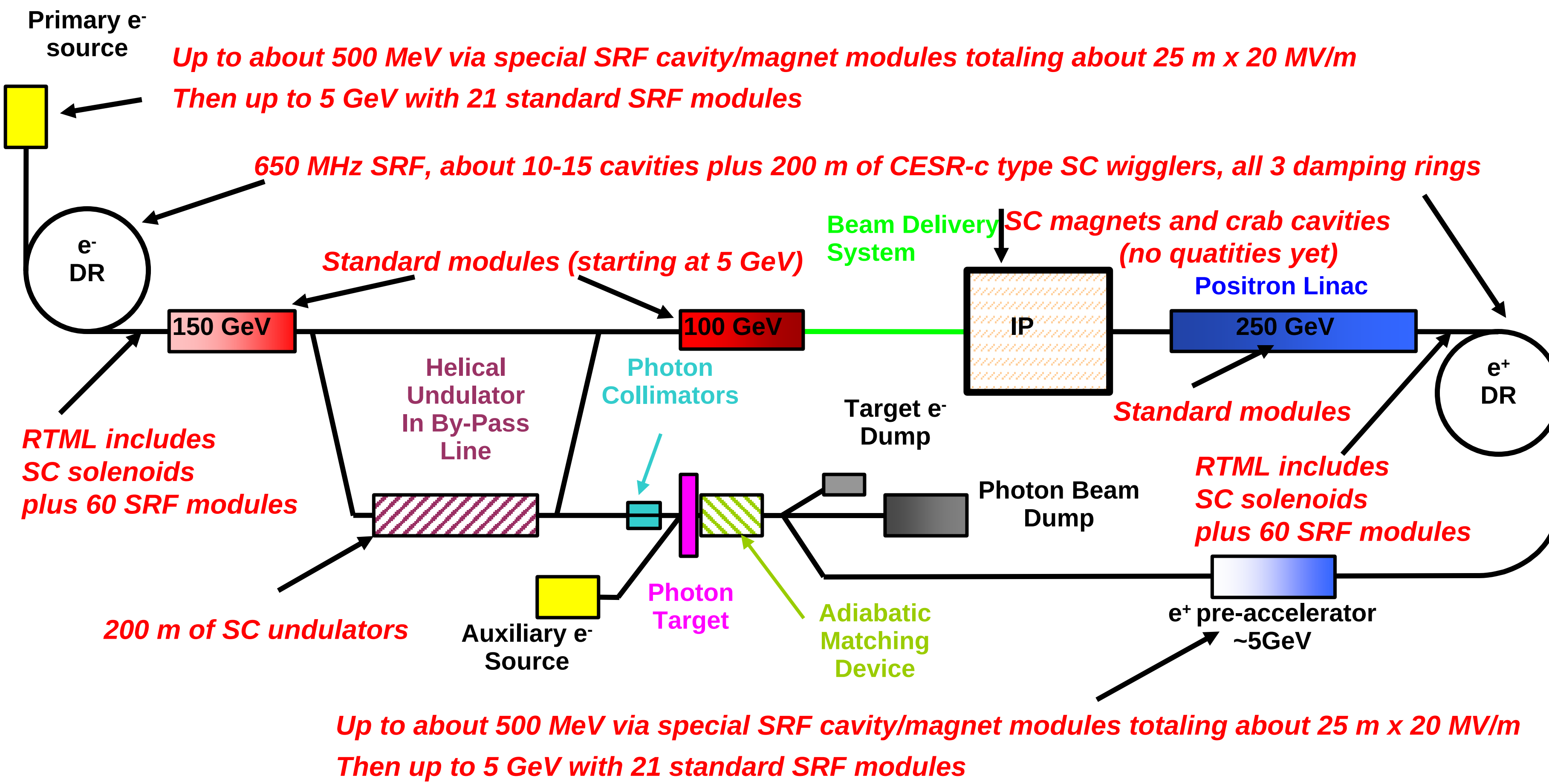
- Control of the 140 meter long string of 96 helium vessels filled in series flow
  - Long time constants
  - Dynamic heating is large
- Changing heat loads at all temperature levels impacts cold box operation
- Warm-up and cool-down of 2.3 km long system
  - Maintenance, repair, reliability
  - Possible “segmentation” of the long cryogenic units

ILC cryogenics is more than these main linac cryogenic units

- ILC will have many other cold devices other than these regular linear patterns of main linac cryogenic modules

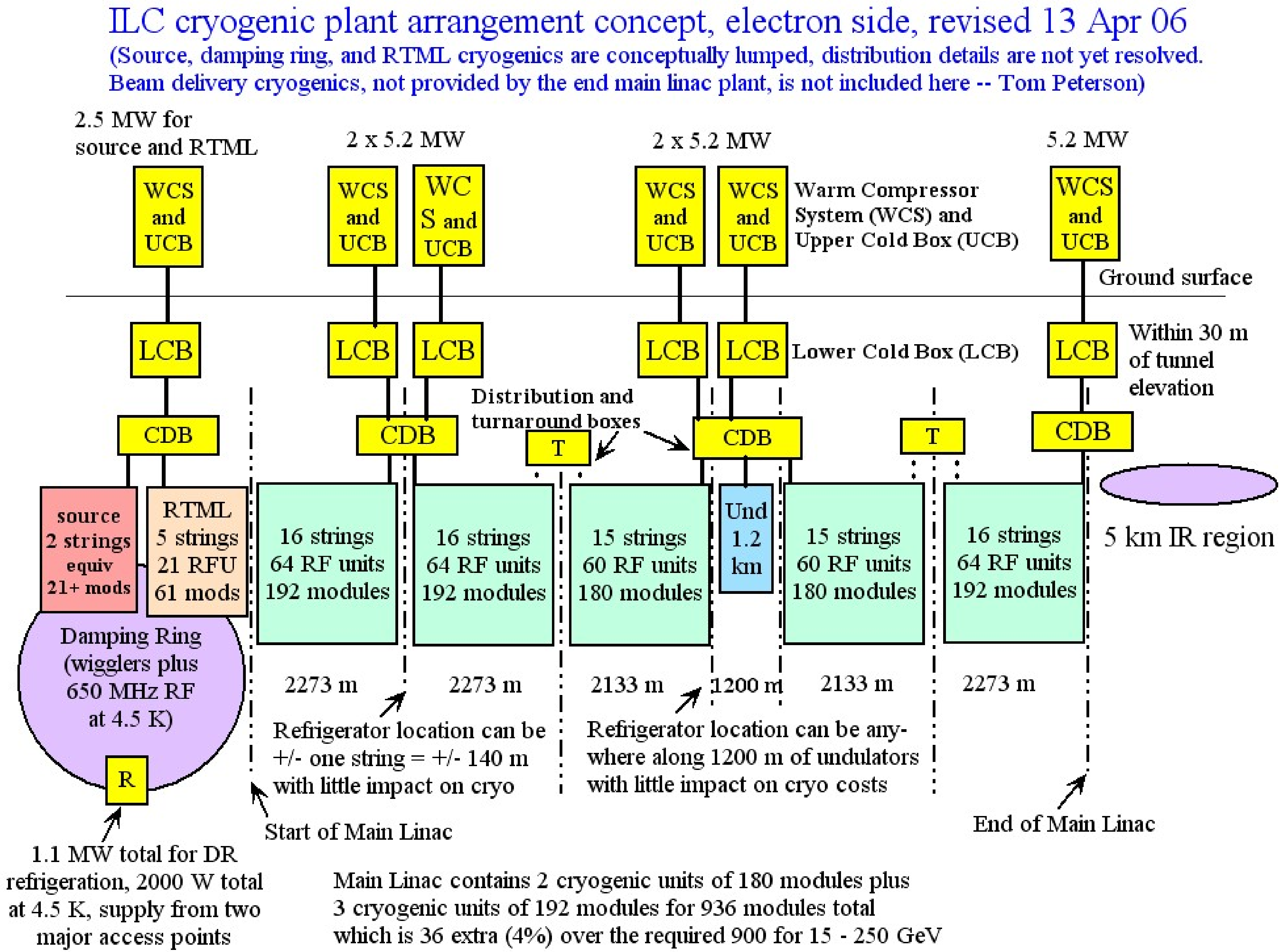
BCD Description -500 GeV Layout-

(Slide lifted from "Positron Source Configuration"
by KURIKI Masao and John Sheppard, January 2006.
Cryogenic device description in red added by Tom Peterson)



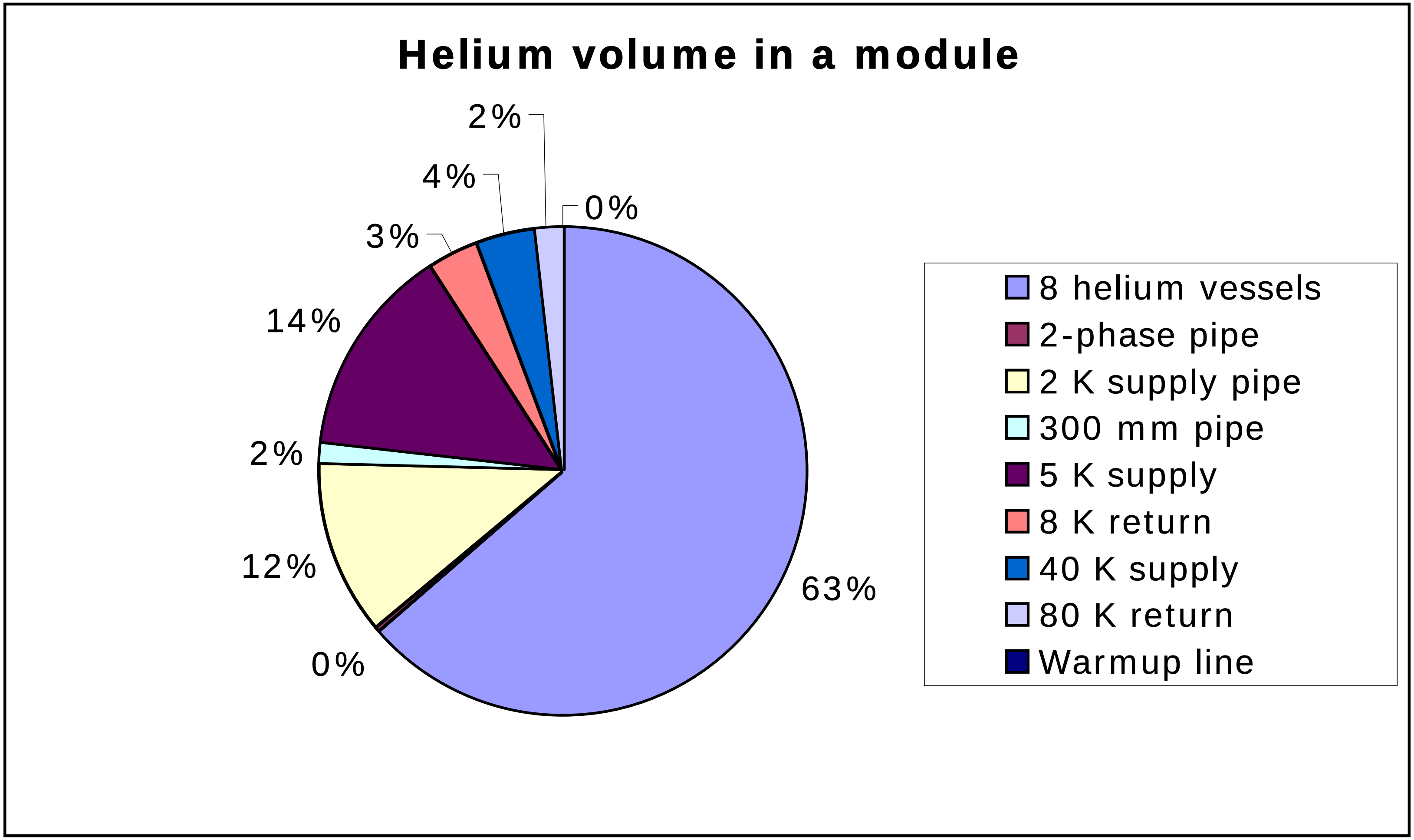
Superconducting devices

- ~936 main linac modules per 250 GeV linac (so 936 x 2)
- Pre-accelerators up to 15 GeV (2 of these)
  - Electron and positron sources -- 21-24 modules (or more) including ~10 special low-energy magnet/RF modules (x 2)
  - RTML -- 60 standard modules, equiv to 5 strings (x 2) plus some SC magnets
- Damping rings (1 electron, 2 positron)
  - Electron side -- 650 MHz SRF, about 15 cavities plus 200 m of CESR-c type SC wigglers = 1200 W total at 4.5 K
  - Positron side -- 650 MHz SRF, about 10 cavities plus 200 m of CESR-c type SC wigglers x 2 rings = 2000 W total at 4.5 K
- 200 meters of SC undulators in electron linac (~300 W)
- SC magnets and crab cavities in interaction regions


ILC cryogenic plant arrangement concept, electron side, revised 13 Apr 06
(Source, damping ring, and RTML cryogenics are conceptually lumped, distribution details are not yet resolved.
Beam delivery cryogenics, not provided by the end main linac plant, is not included here -- Tom Peterson)
2.5 MW for source and RTML
2 x 5.2 MW
2 x 5.2 MW
5.2 MW
WCS and UCB
WCS and UCB
WC S and UCB
WCS and UCB
WCS and UCB
WCS and UCB
Warm Compressor System (WCS) and Upper Cold Box (UCB)
Ground surface
LCB
LCB
LCB
LCB
LCB
LCB
Lower Cold Box (LCB)
Within 30 m of tunnel elevation
Distribution and turnaround boxes
CDB
CDB
T
CDB
T
CDB
source 2 strings equiv 21+ mods
RTML 5 strings 21 RFU 61 mods
16 strings 64 RF units 192 modules
16 strings 64 RF units 192 modules
15 strings 60 RF units 180 modules
Und 1.2 km
15 strings 60 RF units 180 modules
16 strings 64 RF units 192 modules
5 km IR region
Damping Ring (wigglers plus 650 MHz RF at 4.5 K)
R
2273 m
2273 m
2133 m
1200 m
2133 m
2273 m
Refrigerator location can be +/- one string = +/- 140 m with little impact on cryo
Refrigerator location can be any-where along 1200 m of undulators with little impact on cryo costs
Start of Main Linac
End of Main Linac
1.1 MW total for DR refrigeration, 2000 W total at 4.5 K, supply from two major access points
Main Linac contains 2 cryogenic units of 180 modules plus 3 cryogenic units of 192 modules for 936 modules total which is 36 extra (4%) over the required 900 for 15 - 250 GeV

Size comparison to TESLA TDR

- TESLA 500 TDR had 7 large cryoplants
  - 5 at about 5.2 MW and 2 smaller
- ILC 500 looks like about 12 large cryoplants
  - 10 at about 5.2 MW and 2 smaller
- Why more cryoplants in ILC than TESLA?
  - Dynamic load up with gradient squared (length reduced by gradient), larger multipliers, lower plant efficiency


Helium volume in a module
2%
4%
0%
3%
14%
2%
12%
0%
63%
8 helium vessels
2-phase pipe
2 K supply pipe
300 mm pipe
5 K supply
8 K return
40 K supply
80 K return
Warmup line

ILC cryogenic system inventory

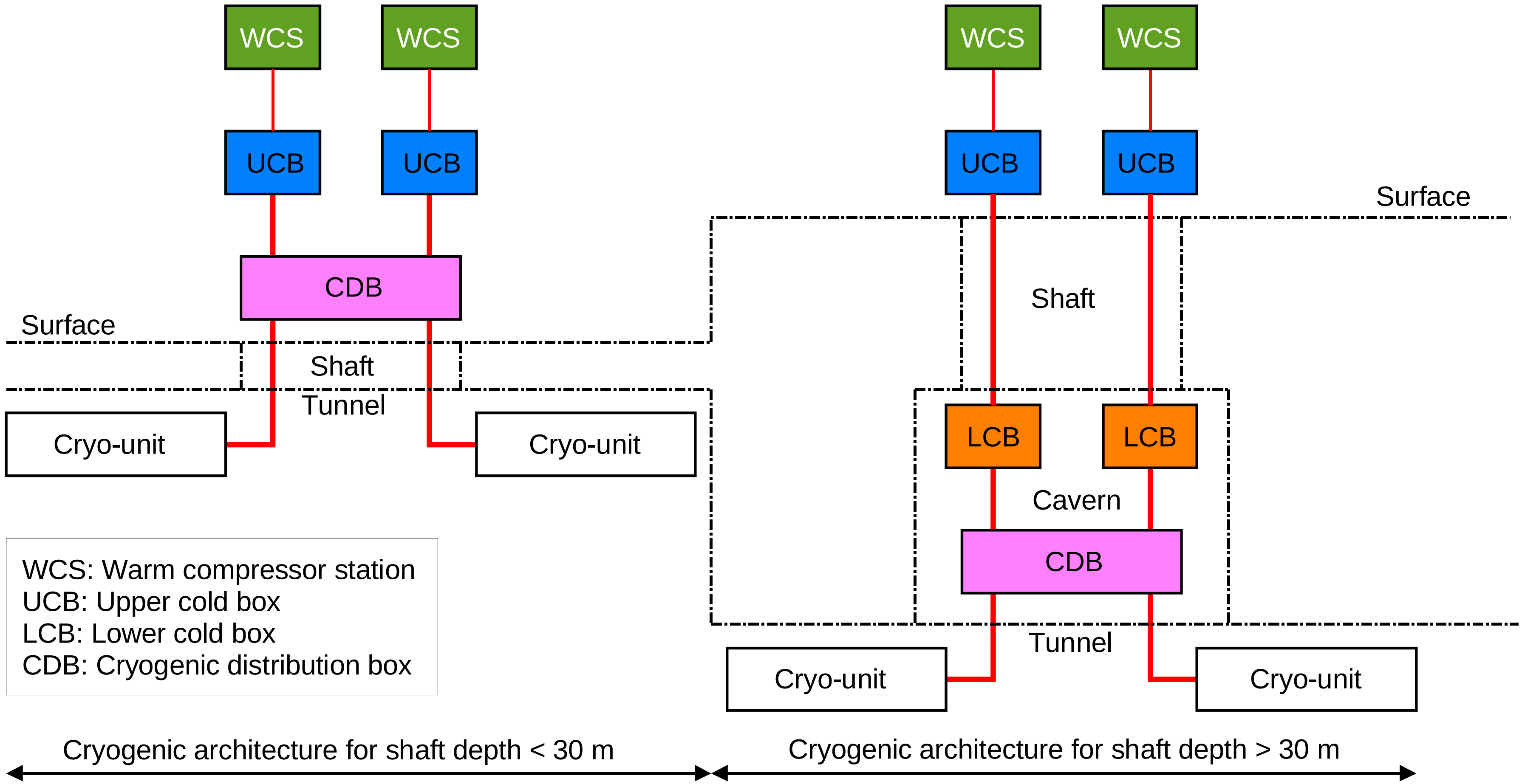
Volumes		Helium (liquid liters equivalent)	Tevatron equivalents	LHC equivalents	Inventory cost (K$)
One module		336.6			
String	12 modules	4038.8	0.1		12.12
Cryogenic unit	16 strings	64621.4	1.1	0.1	193.86
ILC main linacs	2x5 cryo units	646213.9	10.8	0.8	1938.64

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

14 large cryogenic plants

- Compressor systems (electric motors, starters, controls, screw compressors, helium purification, piping, oil cooling and helium after-cooling)
- Upper cold box (vacuum-jacketed heat exchangers, expanders, 80 K purification)
- Lower cold box (vacuum-jacketed heat exchangers, expanders, cold compressors)
- Gas storage (large tank “farms”, piping, valves)
- Liquid storage (a lot, amount to be determined)

Cryogenic architecture



For shaft depth above 30 m, the hydrostatic head in the 2 K pumping line becomes prohibitive and active cryogenics (e.g. cold compressor system) has to be installed in caverns (LBC), i.e. additional cost for cryogenics and civil engineering.

Major cryogenic distribution components

- 10 large (2 K system) tunnel service or "feed" boxes
  - Connect refrigerators to tunnel components
- 10 large (2 K) tunnel distribution or "turnaround" boxes
  - Terminate and/or cross-connect cryogenic units
- ~170 large (2 K) string end boxes of several types
  - Contain valves, liquid collection vessels, instrumentation, some with vacuum breaks
- ~3 km of large transfer lines (including 2 Kelvin lines)
- ~100 "U-tubes" (removable transfer lines)
- Damping rings are two 4.5 K systems each the size (in terms of accelerator layout) of the Tevatron
  - Various distribution boxes and ~10 km of small transfer lines

Production test cryogenics

- Cavity production test dewars
  - Many large, vacuum jacketed dewars for vertical testing of the bare 9-cell niobium cavities
  - Complex cryogenic distribution system
- Module production test stands
  - Many test stands with various cryogenic distribution and service boxes for module production tests
- Cryogenic plants for production tests
  - Vertical dewar testing is larger load than modules
  - Minimally, 4 kW at 40-80 K, 500 W at 4 K, plus 6 gr/sec liquefaction or 300 W at 2 K

References

- TESLA TDR -- online as TESLA Report 2001-23 at http://tesla.desy.de/new_pages/TESLA/TTFnot01.html
- Navigate to other TESLA and TTF documents going back to 1993 from the same web page
- Various CERN LHC cryogenic system documents
- ILC BCD documents
  - http://www.linearcollider.org/wiki/doku.php?id=bcd:bcd_home
  - bcd:main_linac:ilc_bcd_cryogenic_chapter_v3.doc
- ILC presentations
  - Navigate from ILC home page via “Calendar/Past Events” and “Calendar/GDE Meetings”
  - http://www.linearcollider.org/cms/?pid=1000012
- See also my web postings at http://tdserver1.fnal.gov/peterson/tom/refmenu.htm