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ILC Cryogenic Systems Status

Tom Peterson
for the cryogenics global group
13 July 2006

Sources of information

- **TESLA TDR**
- **XFEL talks and reports**
  - » Most recently, "XFEL civil and cryoplant", by Wilhelm Bialowons and Bernd Petersen at http://ilcagenda.cern.ch/conferenceDisplay.py?confId=366
- **Bernd Petersen, et. al. (DESY) direct communications**
- **Tuesday morning systems status webex/teleconference presentations and discussions**
  - » http://ilcagenda.cern.ch/categoryDisplay.py?categId=58
- **Tuesday morning CF&S videoconferences**
  - » Also direct communications with Tom Lackowski, Emil Huedem, and others

Main linac information

- **Mostly by direct communication**
  - » Chris Adolphsen
  - » Nikolay Solyak
- **And from TESLA TDR and XFEL concepts**

RTML information

- **Very informative and up-to-date wiki page with information about the cryogenics requirements for the RTML, at**
  - » http://www.linearcollider.org/wiki/doku.php?id=rdr:rdr_as:rtml_cryo

Damping ring information

- **Damping ring cryogenic component arrangement and heat load estimates are taken from “DR Design Status”, a talk by S. Guiducci at the DR System Area Status Videoconference on 4 April 06.**
  - » http://ilcagenda.cern.ch/conferenceDisplay.py?confId=308
- **Also useful discussions with Richard Ehrlich and Eric Smith of Cornell about CESR RF cavity cooling**

e- and e+ source information

- Electron source parts list
  http://www.linearcollider.org/wiki/doku.php?id=rdr:rdr_as:rdr_as_home
- POSITRON_Tuesday_Review_April.ppt by John Sheppard, presented on April 11.
  http://ilcagenda.cern.ch/conferenceDisplay.py?confId=309

ILC cryogenic system definition

- **The cryogenic system is taken to include cryogen distribution as well as production**
  - » Cryogenic plants and compressors
    - Including evaporative cooling towers
  - » Distribution and interface boxes
    - Including non-magnetic, non-RF cold tunnel components
  - » Transfer lines
  - » Cryo instrumentation and cryo controls
- **Production test systems will also include significant cryogenics**
  - » We are providing input to those cost estimates

ILC cryomodule count

Cryomodules	Number per system	Number of systems	Total device count	Total each type	Type	Description
Main Linac	936	2	1872	624	standard	with quad
				1248	standard	without quad
RTML	60	2	120	64	standard	with quad
				56	standard	without quad
e- source	21	1	21	11	standard	with quad
				4	special	6 cavities + 6 quads
				6	special	8 cavities + 2 quads
e* booster	22	1	22	12	standard	with quad
				4	special	6 cavities + 6 quads
				6	special	8 cavities + 2 quads
e+ Keep Alive	2	1	2	2	special	with quad(s)
Damping Rings	32	3	96	96	special	650 MHz
undulator	13	1	13	4	standard	with quad
				9	standard	without quad
Sum total standard with quad				715		
Sum total standard without quad				1313		
Sum total 1.3 GHz non-standard				22		

ILC superconducting magnets

- **737 1.3 GHz modules have SC magnets**
- **Some SC magnets are outside of RF modules**
  - » 200 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 sections of wigglers, 10 wigglers per section x 2.5 m per wiggler
  - » Some magnets in sources and in RTML (spin rotator, etc.)

End boxes and service boxes

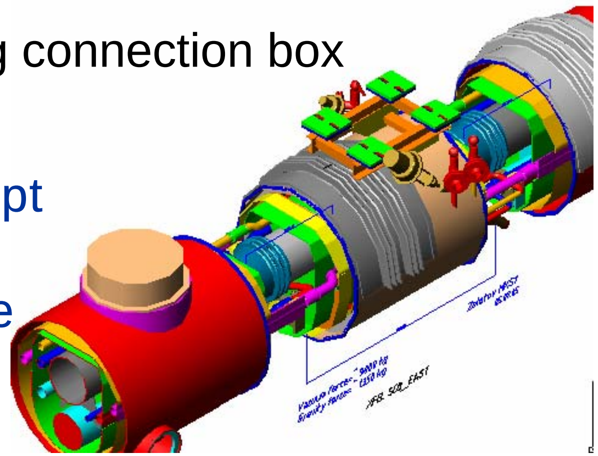
- **String end boxes are short, separate cryostats with approximately the same cross-section as a module**
- **Cryogenic unit end boxes (or “service” boxes) are mostly offset from the beamline to reduce drift space length between cryogenic units**
  - » A cavern (20 meters long) will be required at each cryogenic unit end to accommodate these offset boxes
- **The following two XFEL slides and TTF photo illustrate the concepts for string end boxes and unit service boxes**

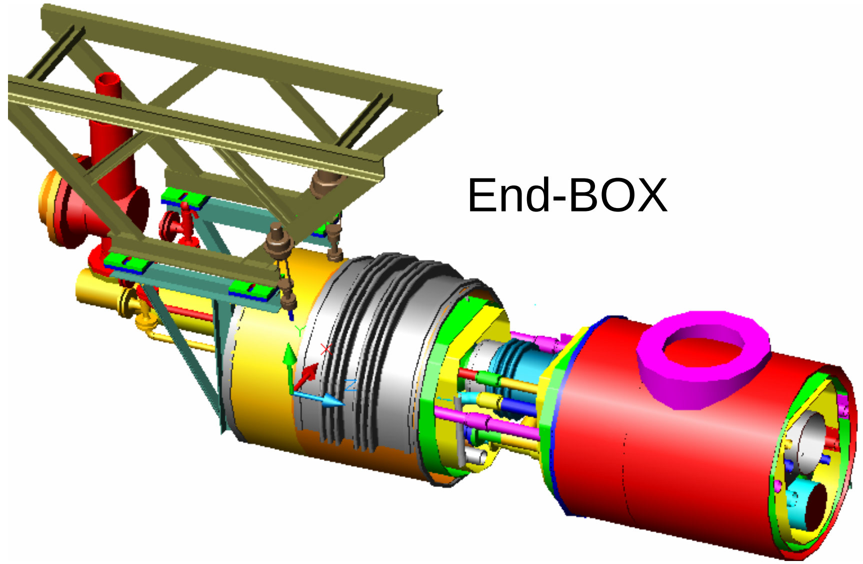
XFEL linac cryogenic components

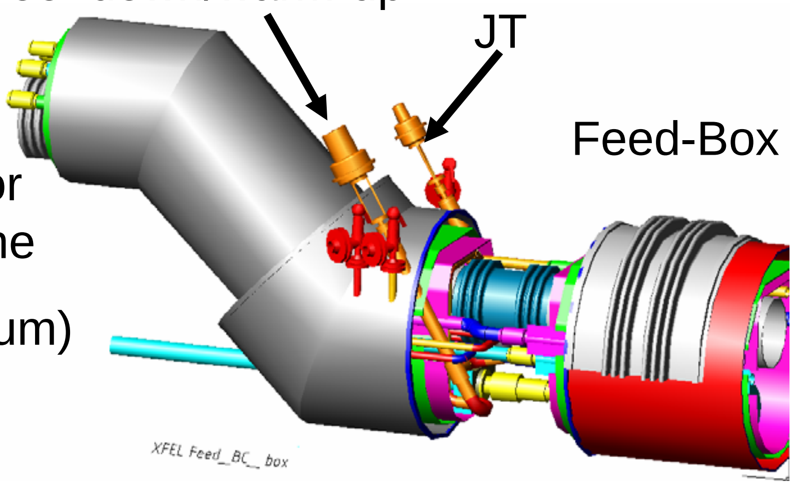
This slide from XFEL_Cryoplant_120506.ppt
by Bernd Petersen

‚regular‘ string connection box

The ILC string end box concept is like this -- a short, separate cryostat







Bunch Compressor
Bypass Transferline

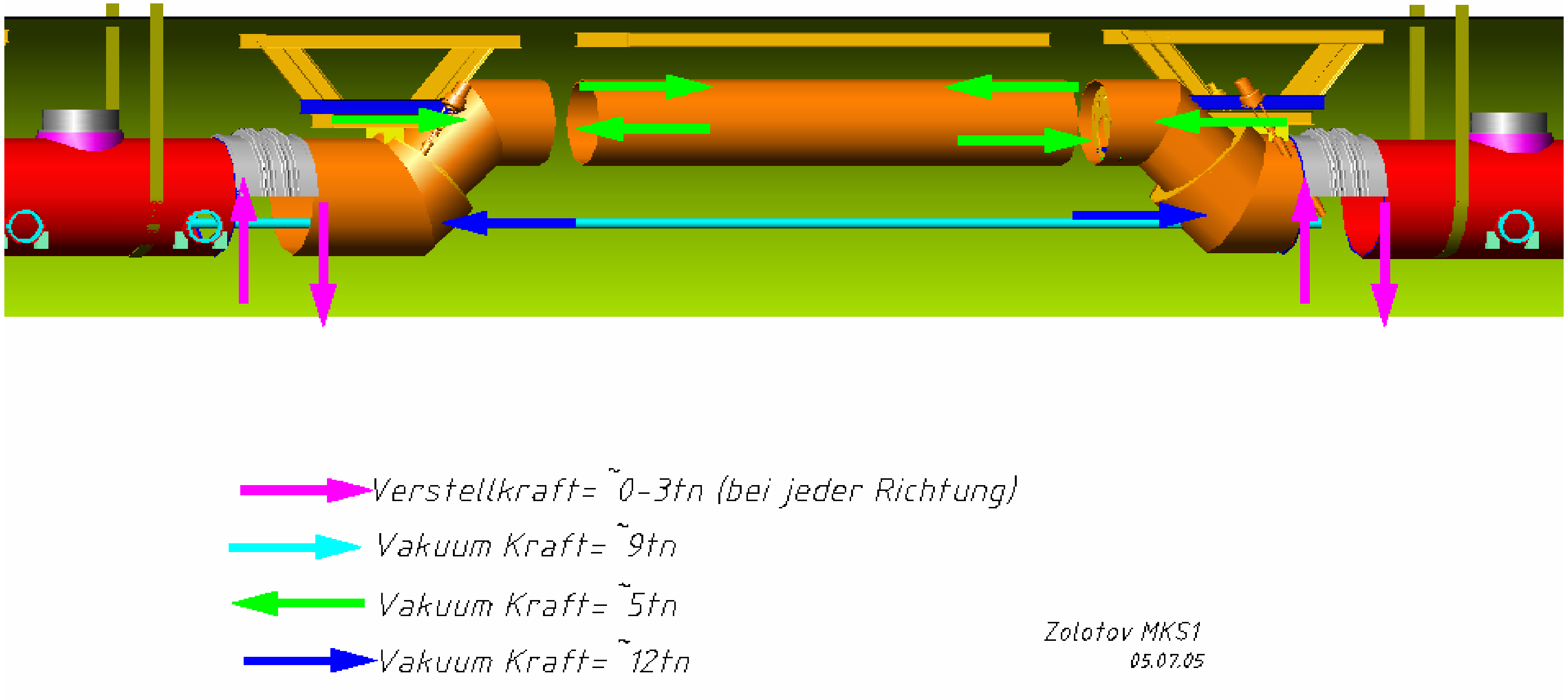
(only 1-phase helium)

The ILC cryogenic unit service boxes may be offset from the beamline, reducing drift space length, with a concept like this.

XFEL Bunch-Compressor-Transferlines

This slide from XFEL_Cryoplant_120506.ppt by Bernd Petersen

The cryogenic unit service boxes may be offset from the beamline as shown, but they would be larger. Drift space is reduced to about 2 meters on each end plus warm drift space.



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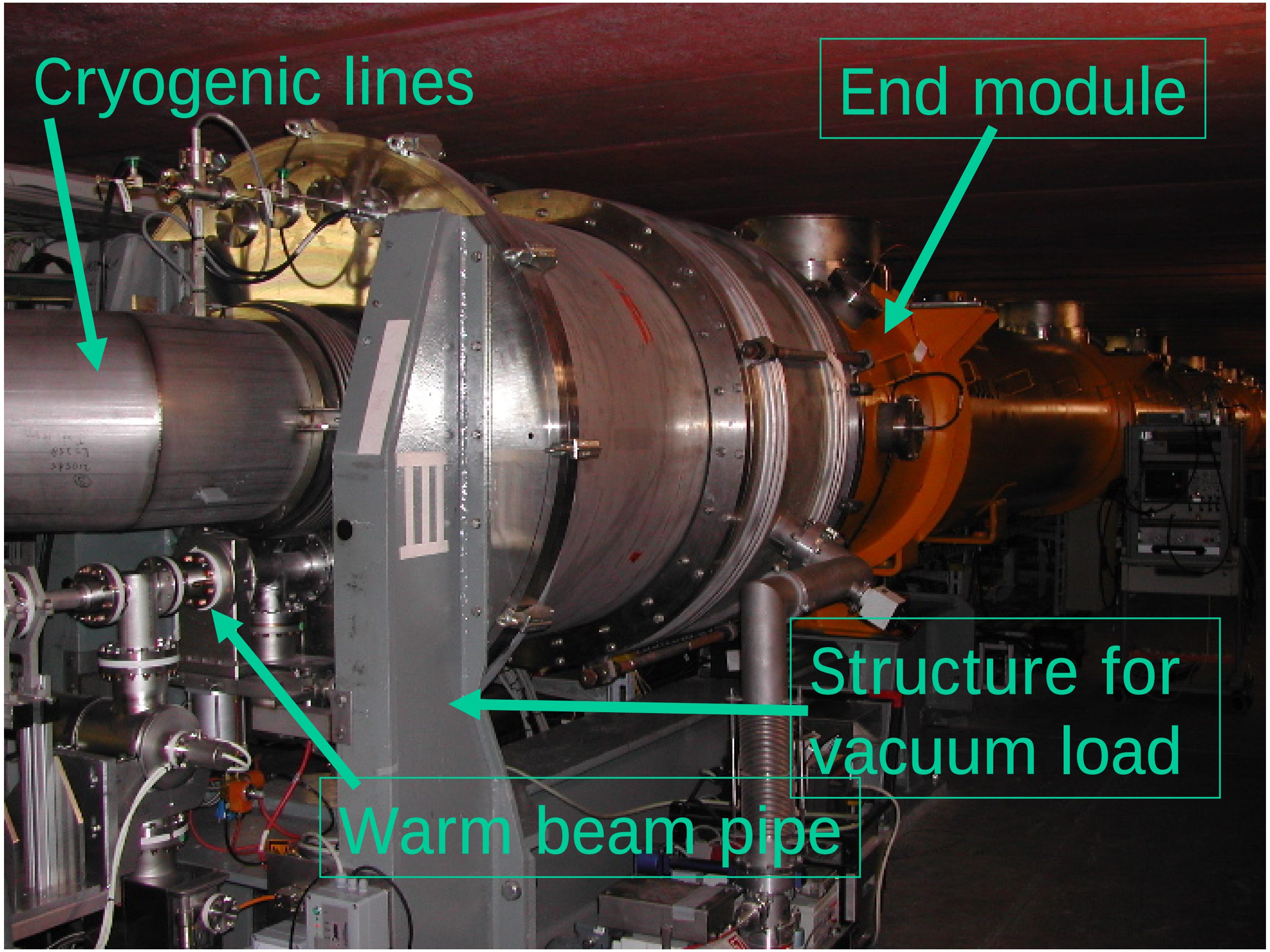
TTF cold-warm transition ~ 2 m



Main linac modules

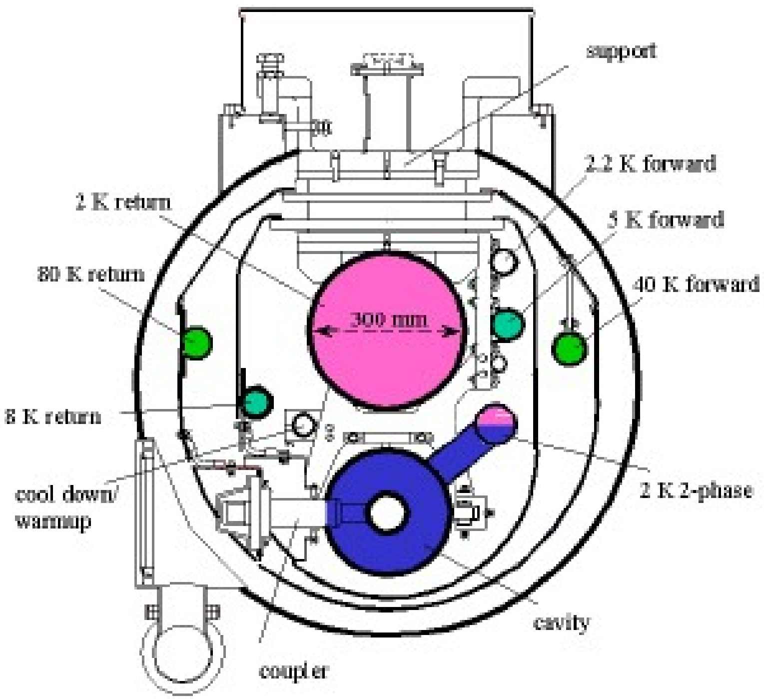
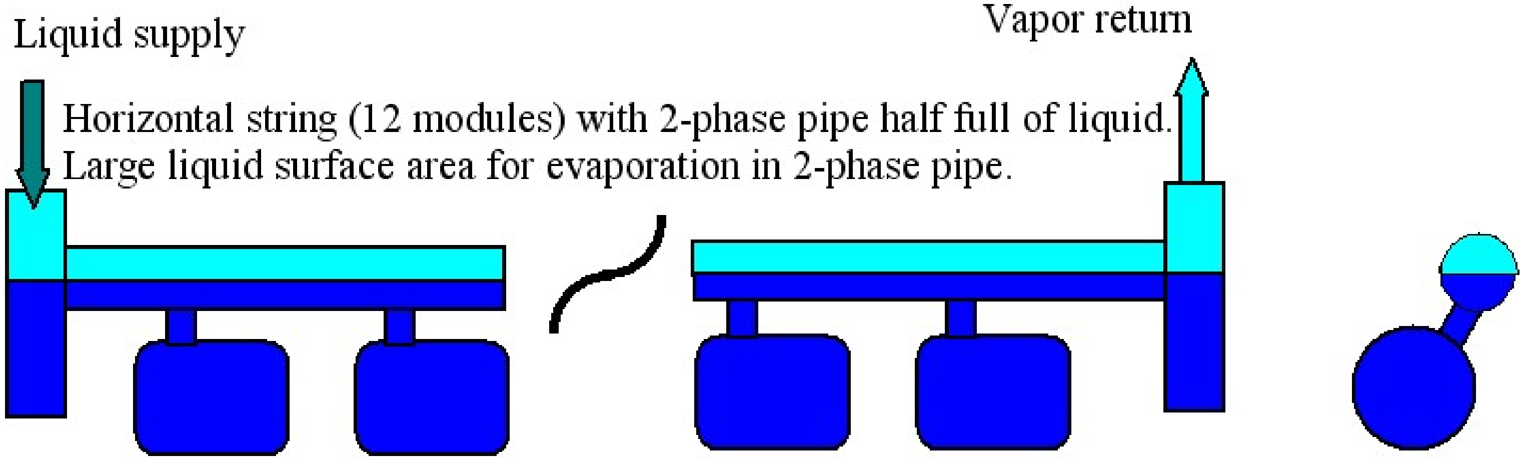


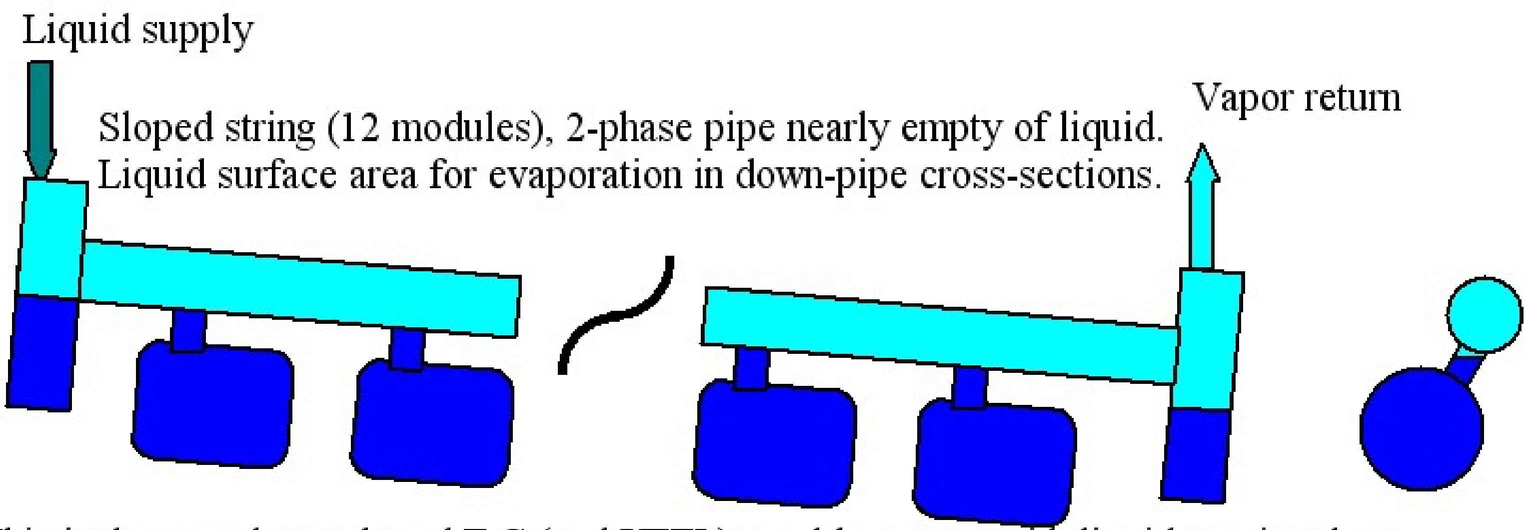
Figure 3.2.11: *Cross section of cryomodule.*

- **Maintain liquid level in helium vessels over a 143 m string length**
- **Pipes sized for pressure drops in 2.3 km cryogenic unit**
- **Very limited cryogenic instrumentation**

Helium vessel liquid management



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



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.

Cryogenic instrumentation

- **RF unit (~8 total thermometers per RF unit)**
  - » Temperature sensors on magnet current leads
  - » Temperature sensor on one helium vessel per module
  - » Temperature sensor on quad helium vessel
- **String end box**
  - » 18 temperature sensors
  - » 2 liquid level sensors
  - » 2 flow sensors
  - » 5 pressure taps (tube to room temperature sensor)
  - » 2 heater controllers
  - » 3 valve controllers
  - » Vacuum gauges

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**

- **Heat load estimates are still under development**
  - » May go lower with better understanding of HOM dynamic load scaling from TESLA
  - » May go higher as discover forgotten sources of heat

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 multiplier
Overcapacity factor		1.40	1.40	1.40	
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 2.23 km long cryogenic unit -- 5 units per 250 GeV linac**
  - » Divides linac nicely for undulators at 150 GeV

Main linac lengths

modules

RF unit (lengths in meters)

without quad	with quad	without quad
11.271	12.543	11.271

three modules

string (vacuum length)

RF unit	RF unit	RF unit	RF unit	end box
35.085	35.085	35.085	35.085	2.500

twelve modules plus string end box

possible segmentation unit

string	string	string	string
142.842	142.842	142.842	142.842

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

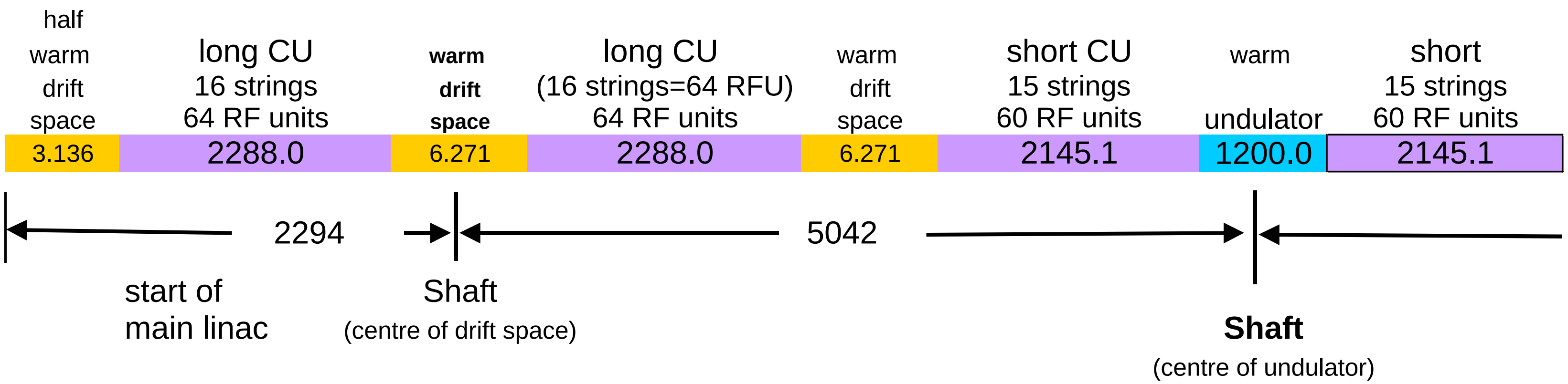
Cryogenic Unit

service box end	segment	segment	segment	segment	service box end
2.500	571.366	571.366	571.366	568.866	2.500

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

2288.0 meters

Main linac warm drift space



- **Presently 6.27 meters warm drift space, only between cryogenic units**
  - » Result of discussions with Nikolay Solyak
  - » Desire to minimize drift length
  - » Arbitrarily one module length minus 2.5 meter transition on each end
- **From cryogenics viewpoint, no strong preference for lengths -- determine from main linac, instrumentation, vacuum input**

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Calculations of the pressure drops in the ILC Cryo Unit

Conclusions (based on inputted data):

Initial parameters A:

P inlet =	1.20	Bar
T inlet =	2.40	K
Heat =	0.02	W/m
Length =	3.00	km
Flow =	0.15	kg/s
ID =	0.06	m

Final parameters A

P outlet=	1.17	Bar
T outlet =	2.59	K
Heat =	0.02	W/m
Length =	3.00	km
Flow =	0.15	kg/s
ID =	0.06	m

Initial parameters B:

P inlet =	0.03	Bar
T inlet =	2.100	K
Heat =	0.01	W/m
Length =	3.00	km
Flow =	0.15	kg/s
ID =	0.30	m

init qual =	1	none
T vapor =	1.986	K
h vapor =	24982.3	J/kg
init flow =	0.01	kg/s

Final parameters B:

P outlet=	0.03	Bar
T outlet =	2.00	K
Heat =	0.01	W/m
Length =	3.00	km
Flow =	0.15	kg/s
ID =	0.30	m

Initial parameters C:

P inlet =	5.00	Bar
T inlet =	5.00	K
Heat =	1.17	W/m
Length =	3.00	km
Flow =	0.23	kg/s
ID =	0.07	m

Final parameters C - initial parameters D:

P outlet=	4.85	Bar
T outlet =	6.63	K
Heat =	1.17	W/m
Length =	3.00	km
Flow =	0.23	kg/s
ID =	0.07	m

Final parameters D:

P outlet=	4.57	Bar
T outlet =	8.03	K
Heat =	1.17	W/m
Length =	3.00	km
Flow =	0.23	kg/s
ID =	0.07	m

Initial parameters E:

P inlet =	16.00	Bar
T inlet =	40.00	K
Heat =	6.68	W/m
Length =	3.00	km
Flow =	0.25	kg/s
ID =	0.07	m

Final parameters E - initial parameters F:

P outlet=	14.90	Bar
T outlet =	55.09	K
Heat =	6.68	W/m
Length =	3.00	km
Flow =	0.25	kg/s
ID =	0.07	m

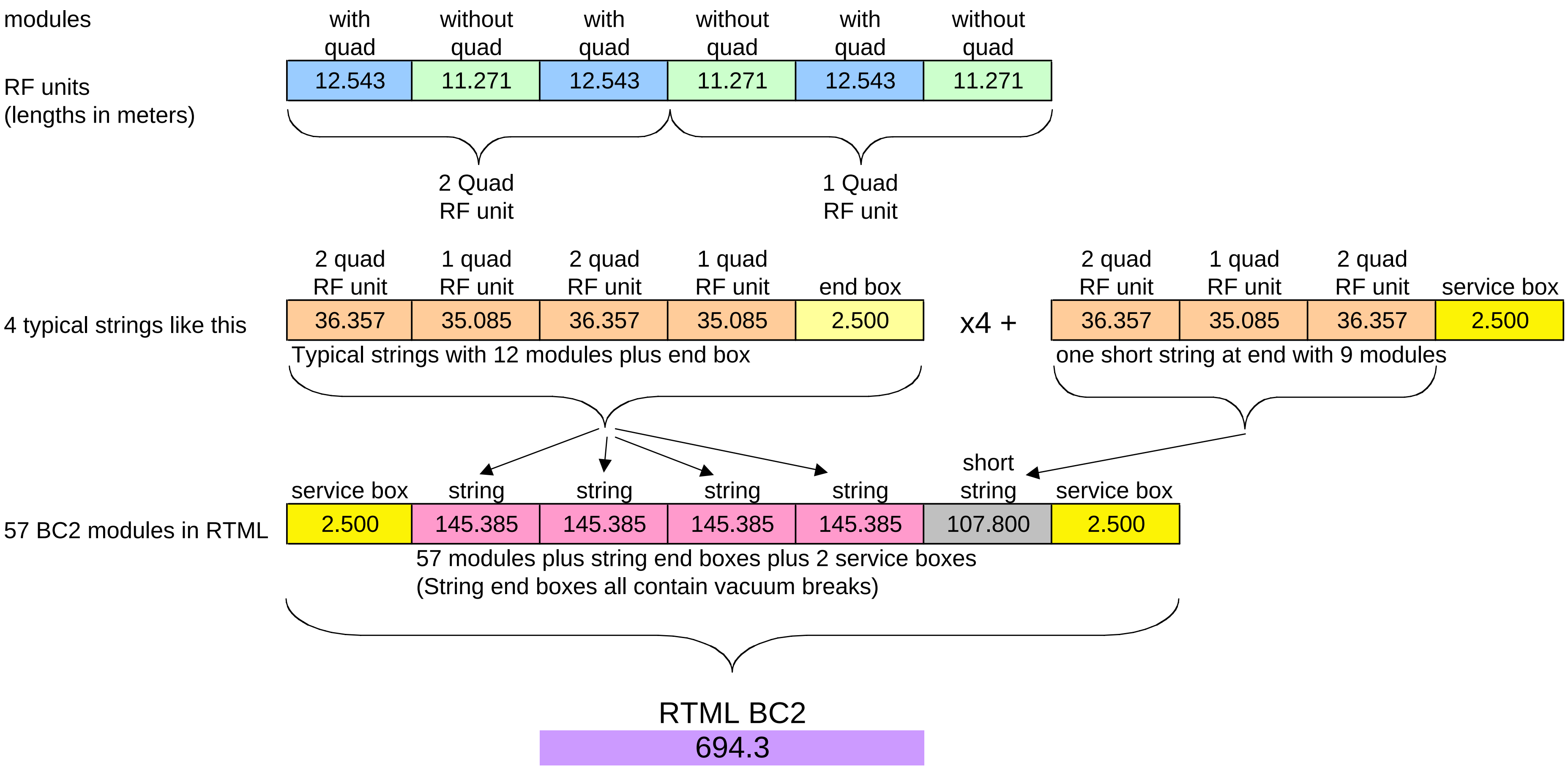
Final parameters F:

P outlet=	13.22	Bar
T outlet =	76.89	K
Heat =	9.51	W/m
Length =	3.00	km
Flow =	0.25	kg/s
ID =	0.07	m

Module pipe sizes updated

Pipe function	BCD name	TTF inner diameter (mm)	XFEL plan inner diameter (mm)	**ILC proposed inner dia (mm)**	ILC pressure drop
2.2 K subcooled supply	A	45.2	45.2	**60**	30 mbar
Major return header, structural supp't	B	~300	~300	**~300**	1.5 mbar
5 K shield and intercept supply	C	57.5	71	**70**	
8 K shield and intercept return	D	50.0	71	**70**	0.43 bar
40 – 50 K shield supply	E	57.5	71	**80**	
75 - 80 K shield return	F	50.0	71	**80**	~1.6 bar
2-phase pipe		72.1	72.1	**72.1**	
Helium vessel to 2-phase pipe cross-connect		54.9	54.9	**54.9**	

RTML BC2 follows main linac pattern



Damping ring heat loads

	e- RF module (one cavity per module)	e+ RF module	e- wiggler (2.5 meters)	e+ wiggler (2.5 meters)
Static 4.5 K heat (W)	30.0	30.0	5.0	5.0
Dynamic 4.5 K heat (W)	18.0	41.0	0.0	0.0
Number per location	4	6	10	20
Total 4.5 K heat per location (W)	192.0	426.0	50.0	100.0
Number of locations	4	4	8	8
Total 4.5 K heat per damping ring (W)	768.0	1704.0	400.0	800.0
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 location	4	6	10	20
Total 70 K heat per location (W)	240.0	360.0	500.0	1000.0
Number of locations	4	4	8	8
Total 70 K heat per damping ring (W)	960.0	1440.0	4000.0	8000.0

Notes: e+ has 3 RF modules in each ring at each location x 2 rings
e+ has 10 wigglers in each ring at each location x 2 rings

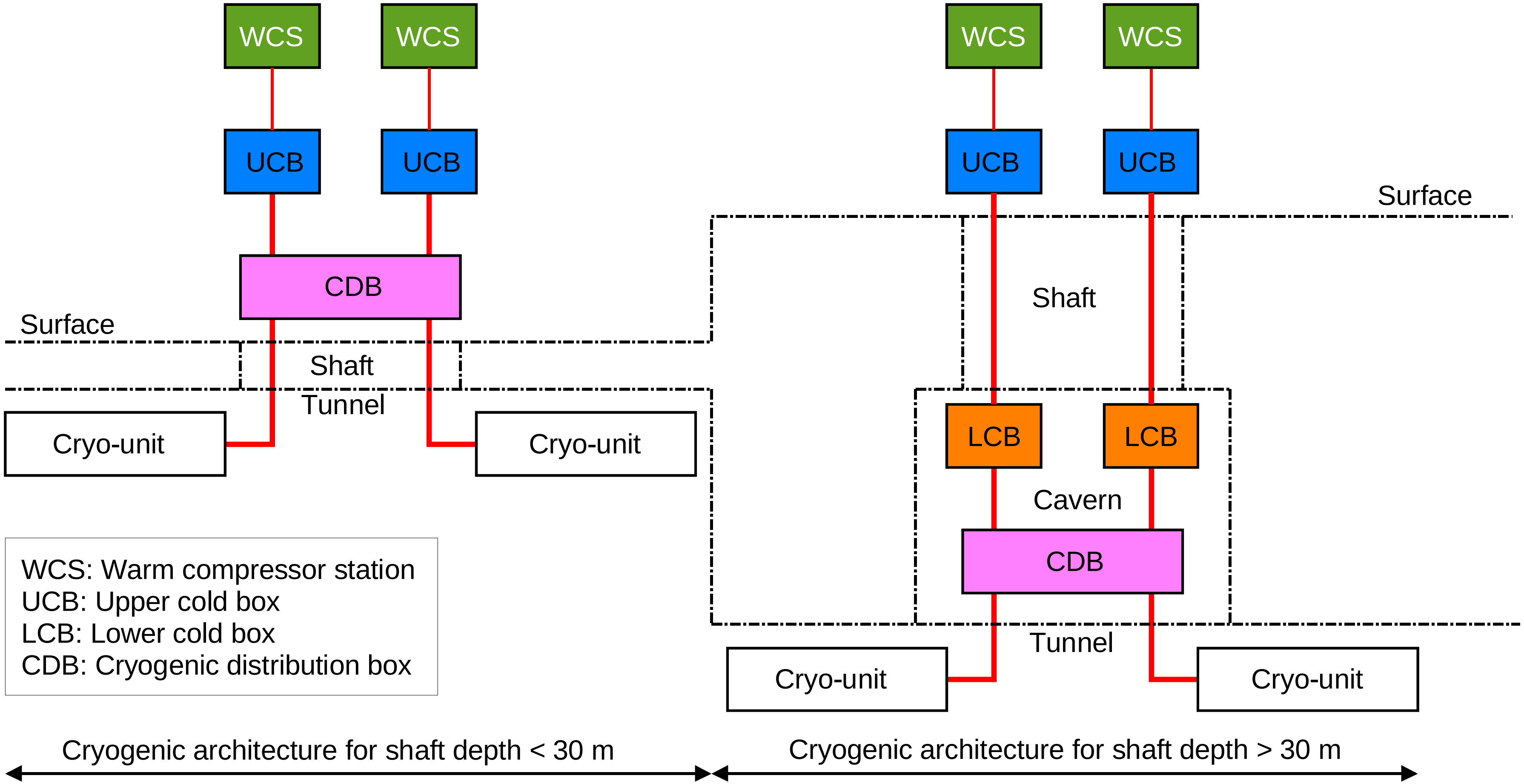
Damping ring cryo system concept

- **Four cryo plants located around each damping ring, one at each RF location**
- **Each plant provides the liquid for 4.5 K bath cooling of the RF and wiggler magnets and the nominally 70 K shield**
- **At least part of each plant is underground, at tunnel elevation, in caverns which also provide RF power, etc.**
- **Wigglers are in 8 locations**
  - » Each plant supplies two sets of wigglers, one 4.5 K / 70 K transfer line goes 1/8 of the way around the damping ring, through the tunnel from each plant, to the remote wigglers

Damping ring cryo plant sizes

		electron ring 40 K to 80 K Temperature level	electron ring 4.4 K Temperature level		positron ring 40 K to 80 K Temperature level	positron ring 4.4 K Temperature level
Temp in	(K)	40.00	4.4		40.00	4.4
Press in	(bar)	16.0	1.2		16.0	1.2
Total predicted heat per cryogenic unit	(W)	1580.00	504.00		1580.00	688.00
Number of cryogenic units per location		1	1		2	2
Total predicted heat per location	(W)	1580.0	504.0		3160.0	1376.0
Heat uncertainty factor (on static only)		1.50	1.50		1.50	1.50
Design heat load per location	(W)	2330.00	684.00		4660.00	1736.00
Design mass flow per location	(g/s)	11.17	35.01		22.33	88.84
Design ideal power	(W)	10729.6	45795.8		21459.2	116230.3
4.5 K equiv design power	(W)	163.4	697.5		326.8	1770.2
Efficiency (fraction Carnot)		0.20	0.20		0.20	0.20
Efficiency in Watts/Watt	(W/W)	23.0	334.8		23.0	334.8
Nominal operating power	(kW)	53.6	229.0		107.3	581.2
Overcapacity factor		1.40	1.40		1.40	1.40
Overall net cryogenic capacity multiplier		2.06	1.90	1.93	2.06	1.77
Installed power	(kW)	75.1	320.6		150.2	813.6
Installed 4.5 K equiv	(kW)	0.3	1.5		0.7	3.7
Percent of total power at each level		19.0%	81.0%		15.6%	84.4%
Total operating power for one location (MW)			0.28			0.69
Total installed power for one location (MW)			0.40			0.96
Total installed 4.5 K equivalent power for one location (kW)			1.81			4.40
Fraction of largest practical cryoplant for location			0.07			0.18
Total installed power for damping ring(s) (MW)			1.58			3.86

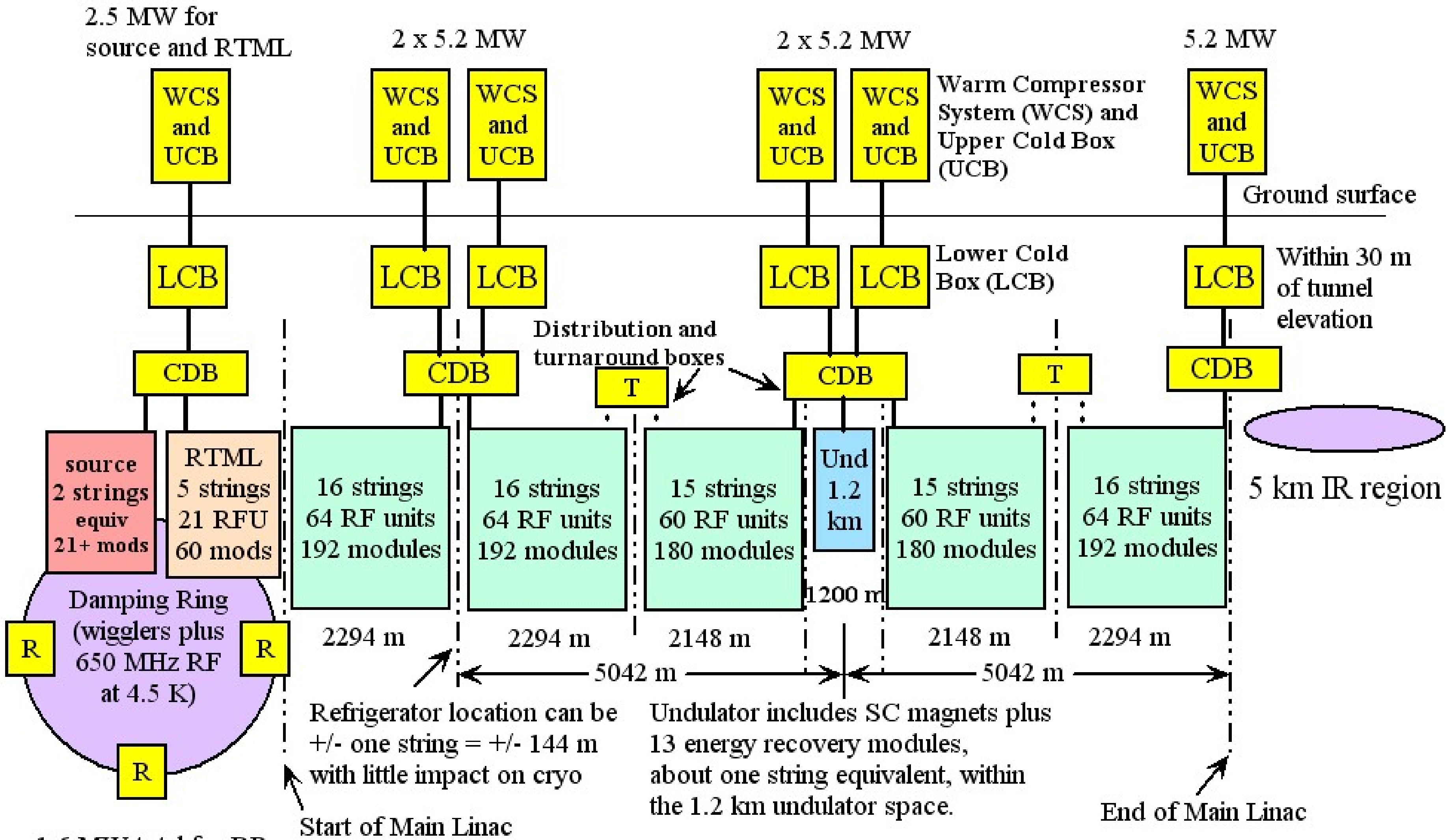
Cryogenic architecture



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.

ILC cryogenic plant arrangement concept, electron side, revised 9 June 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)



1.6 MW total for DR refrigeration, 2000 W equiv total at 4.5 K, supply from four major access points

Main Linac contains 2 cryogenic units of 180 modules plus 3 cryogenic units of 192 modules plus 13 undulator energy recovery modules for 949 modules total, which is 5 extra modules over the required 944 (= 931 for 15 - 250 GeV with 3% overhead and 5 degrees off-crest plus the 13 modules to recover the undulator lost energy).

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

ILC cryogenic plant size summary

- **ILC 500 will have 12 large cryoplants plus 8 smaller ones (not including BDL)**
  - » 10 at about 5.2 MW for the main linacs
  - » 2 at about 2.5 MW for the sources and RTML's
  - » 4 at about 1.0 MW for the positron damping rings
  - » 4 at about 0.4 MW for the electron damping ring
- **Why more cryoplants in ILC than TESLA?**
  - » Dynamic load up with gradient squared (length reduced by gradient), larger multipliers, lower assumptions about plant efficiency

Items associated with 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)

Major cryogenic distribution components

- **8 large (2 K system) tunnel service or "feed" boxes**
  - » Connect refrigerators to tunnel components
- **8 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, heaters, liquid collection vessels, instrumentation, 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 ~7 km of small transfer lines
- **Various special end boxes for isolated SC devices**

Cryogenics WBS levels 4, 5 (cryogenics starts at level 3)

ILC RDR Cryogenic Cost Estimate

Identifier	Item description	basis	Unit	2 x 250 GeV ILC – Materials & Services: No. of units	FY06 M$ per unit	Total M&S M$
1.7.2	**Cryogenic Plant & Distribution**					**$ -**
1.7.2.1	**Cryogenic Plants**					**$ -**
1.7.2.1.1	**Main Linac cryogenic plants**					**$ -**
1.7.2.1.2	**Source and RTML cryogenic plants**					$ -
1.7.2.1.3	**Damping Ring cryogenic plants**					$ -
1.7.2.2	**Cryogenic Distribution**					**$ -**
1.7.2.2.1	**Main Linac cryogenic distribution**					**$ -**
1.7.2.2.2	**Source and RTML cryogenic distribution**					**$ -**
1.7.2.2.3	**Damping Ring cryogenic distribution**					**$ -**

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Example of level 6

Identifier	Item description	basis	Unit	2 x 250 GeV ILC Materials & Services No. of units	FY06 M$ per unit	Total M&S M$
1.7.2	**Cryogenic Plant & Distribution**					**$ -**
1.7.2.1	**Cryogenic Plants**					**$ -**
1.7.2.1.1	**Main Linac cryogenic plants**					**$ -**
1.7.2.1.1.1	Main Linac warm compressor systems		each	10		$ -
1.7.2.1.1.2	Main Linac cooling tower systems		each	10		$ -
1.7.2.1.1.3	Main Linac warm gas storage systems		each	10		$ -
1.7.2.1.1.4	Main Linac upper cold boxes		each	10		$ -
1.7.2.1.1.5	Main Linac lower cold boxes		each	10		$ -
1.7.2.1.1.6	Main Linac vertical transfer line		m			$ -
1.7.2.1.1.7	Main Linac purification system		each	10		$ -
1.7.2.1.1.8	Main Linac installation contracts		each	10		$ -
1.7.2.1.1.9	Main Linac cryogenic control systems		each	10		$ -
1.7.2.1.1.10	Main Linac liquid helium storage systems		each	10		$ -
1.7.2.1.1.11	Main Linac misc. (ODH, gas analysis, instrument air, etc.)		each	10		$ -
1.7.2.1.1.12	Main Linac helium		liters			$ -

Open issues

- **Still identifying cold devices and estimating heat loads in sources and damping rings**
  - » Damping ring cryogenic layout is just a first concept
  - » Need locations of SC devices for sizing transfer lines -- have many but not all
- **Have not dealt with beam delivery system details yet**
- **Want to investigate alternatives for reducing cryo system visibility**
  - » Compressor grouping, inventory storage grouping, pipe sizing, etc.

Plant cost estimates

- **Cost (1998 MCFH) = 2.2*P(4.5 kW equiv)^0.6**
  - » "Economies of Large Helium Cryogenic Systems: Experience from Recent Projects at CERN," S. Claudet, et. al., Advances in Cryogenic Engineering, Vol 45, pg 1301, Plenum Press, 2000.
- **Convert 1998 CFH to 1998 $ and then 1998 $ to 2006 $**
- **Need to scale from 1998 to 2006 with proper factor, to be determined**

Scaling from 1998 costs

- **For example, from CRU stainless steel price index**
  - » http://www.cruspi.com/HomePage.aspx
  - » 1998 to 2005 is factor 1.44 (consumer price index was only 1.16)
  - » Only have data through 2005
  - » Result: Cost (2005 $) = 2.16*P(4.5 kW equiv)^0.6
- **Will also look at aluminum and labor**
- **Other more recent cryo plant cost data are available**
  - » Linde study for Fermilab's ILCTA-New Muon Lab refrigerator implies factor 1.53 for 1998 CHF to 2006 $
  - » SNS, and perhaps others
  - » CERN

Thermal cost optimization

- **Additional 1 W at 2 K per module ==> additional capital cost to the cryogenic system of $4300 to $8500 per module (scale plant costs or scale whole system)**
- **Additional 1 W at 2 K per module ==> additional installed power of 3.2 MW for ILC**
  - » $1100 per year per module operating costs.
  - » There is room in the 2 K pipes for additional flow
- **Low cryo costs relative to module costs suggest that an optimum ILC system cost might involve relaxing some thermal features for ease of fabrication, even at the expense of a few extra watts of static heat load per module.**