Cryomodules as Part of the ILC Cryogenic System

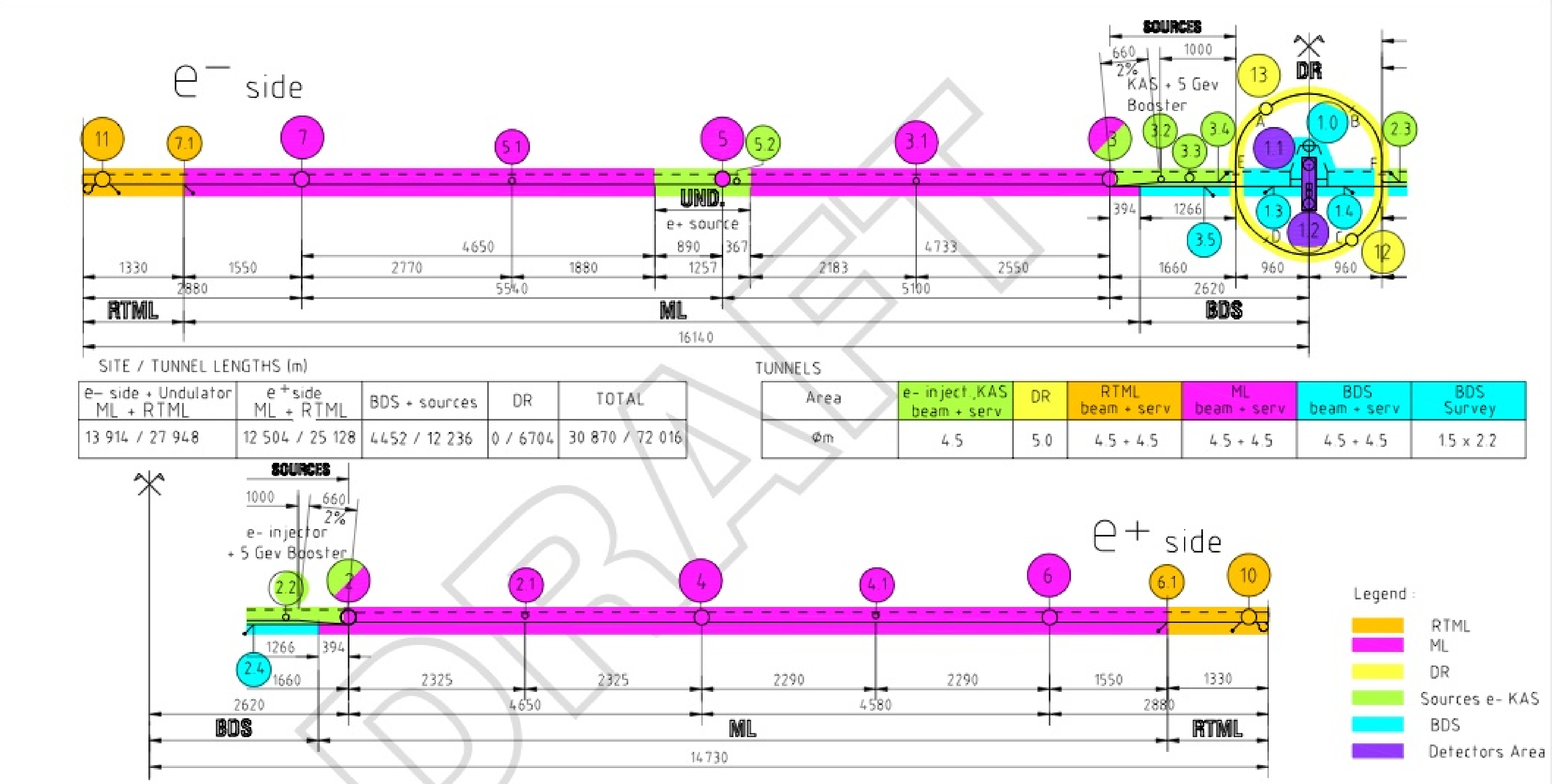
Tom Peterson

Presented at the cryomodule meeting
in Milan

22 January 2007

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 plant controls**
    - Tunnel cryo controls are in the ILC controls estimate
- Production test systems will also include significant cryogenics
  - **We are providing input to those cost estimates**



SITE / TUNNEL LENGTHS (m)

e− side + Undulator ML + RTML	e+ side ML + RTML	BDS + sources	DR	TOTAL
13 914 / 27 948	12 504 / 25 128	4452 / 12 236	0 / 6704	30 870 / 72 016

TUNNELS

Area	e- inject.,KAS beam + serv	DR	RTML beam + serv	ML beam + serv	BDS beam + serv	BDS Survey
Φm	4.5	5.0	4.5 + 4.5	4.5 + 4.5	4.5 + 4.5	1.5 x 2.2

SHAFTS

Point	1.0	1.1	1.2	2	3	3.3	5.2	4	5	6	7	10	11	12/C	13/A
Φm	9	16	16	14	14	4	4	14	14	9	9	14	14	9	9

BORINGS

Point	2.1, 3.1, 4.1, 5.1	2.2, 3.2	1.3, 1.4, 2.4, 3.5
Φm	1.50		

SHAFT BASE CAVERNS

Point	2, 3,	4, 5, 6, 7,	10, 11
(LxWxH) m	49 x 16 x 18 + 3 storeys		

MUON WALL WIDENINGS

Point	1.3, 1.4
(LxWxH) m	25 x7x6 +15x7x6

SOURCES CAVERNS

Point	Undulator 5.2	KAS 3.3	2.2, 3.2
(LxWxH) m	21 161m3	6 574m3	7 X 15 X 7.5

DR ALCOVES

Point	12/C, 13/A	B, D, E, F
(LxWxH) m	75 x 10 x 10 + 1 storey	16 x 8 x 8

DETECTORS HALL

Point	1.1, 1.2	1.0
(LxWxH) m	120 x 25 x 39	40 x 15 x 15

BEAM DUMPS CAVERNS (↖)

Point	SOURCES 2.3, 3.4	RTML 6.1, 7.1, 10, 11	BDS 1.3, 1.4, 2.4, 3.5
(LxWxH) m	5 x 4 x 4		20 x 9 x 15 + 1 storey

BEAM DUMP SERVICE HALLS (↖)

Point	BDS 1.3, 1.4, 2.4, 3.5
(LxWxH) m	30x20x 10

ILC - UNDERGROUND STRUCTURES SCHEMATIC LAYOUT

AREA SYSTEM DIVISION **(2 mobile Detectors - Push Pull - modified CMS procedure)**

EUROPEAN REGION

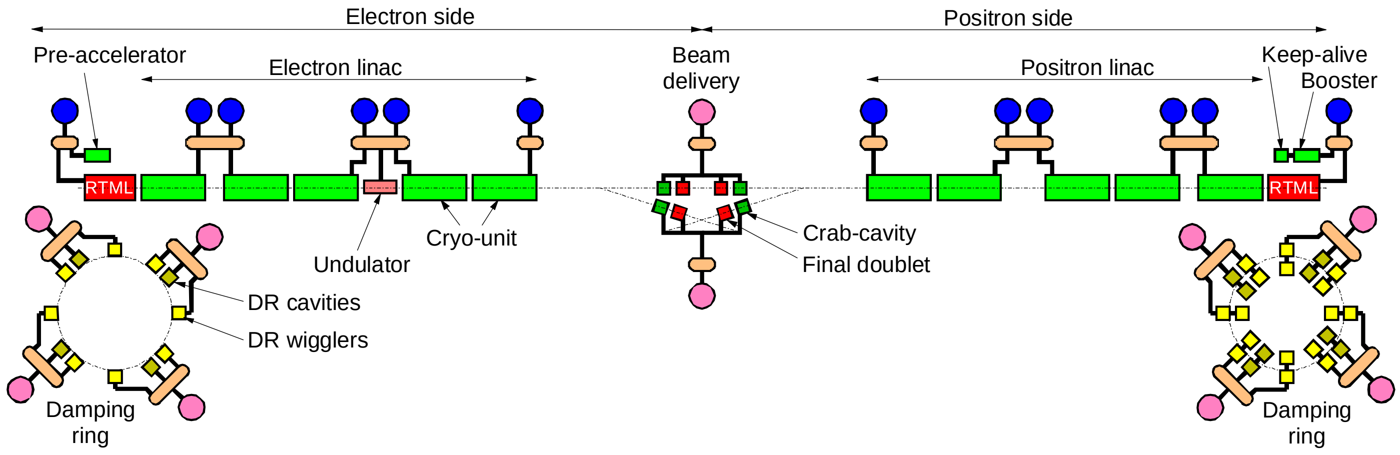
CERN

GROUP : TS-CE
CIVIL ENGINEERING
SUPERVISOR : JL.BALDY
DESIGNER : N.BADDAMS

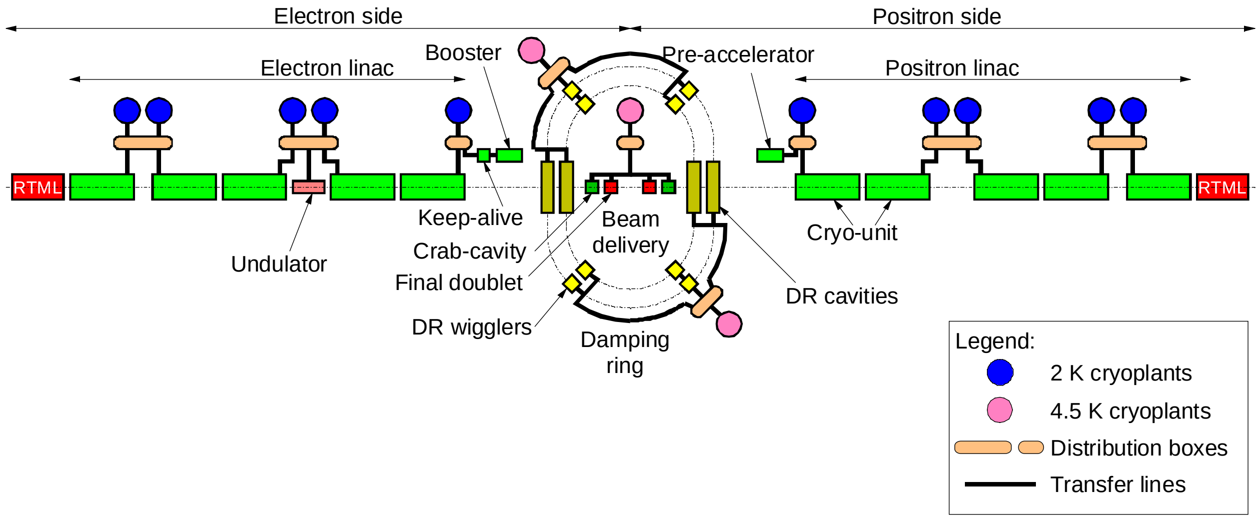
SCALE : 1/50000(A3_FORMAT) DATE : 05_DEC_2006

ILC-.CE-1.1649.0016 SIZE 3 INDICE G

Baseline Configuration Layout



Reference Design Layout



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**

Major cryogenic distribution components

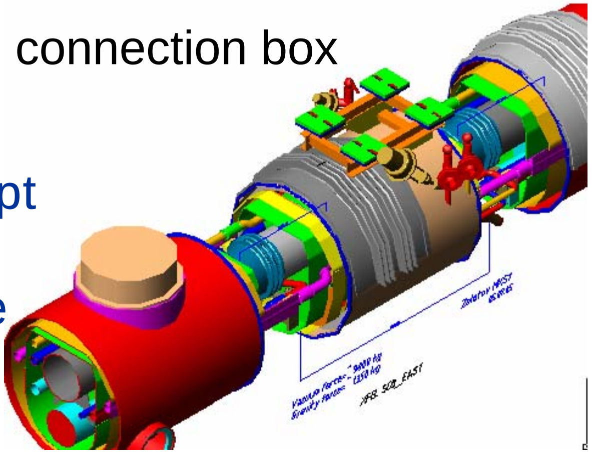
- 6 large (2 K system) tunnel service or “distribution” boxes
  - **Connect refrigerators to tunnel components and allow for sharing load between paired refrigerators**
- 20 large (2 K) tunnel cryogenic unit “feed” boxes
  - **Terminate and/or cross-connect the 10 cryogenic units**
- ~132 large (2 K) 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

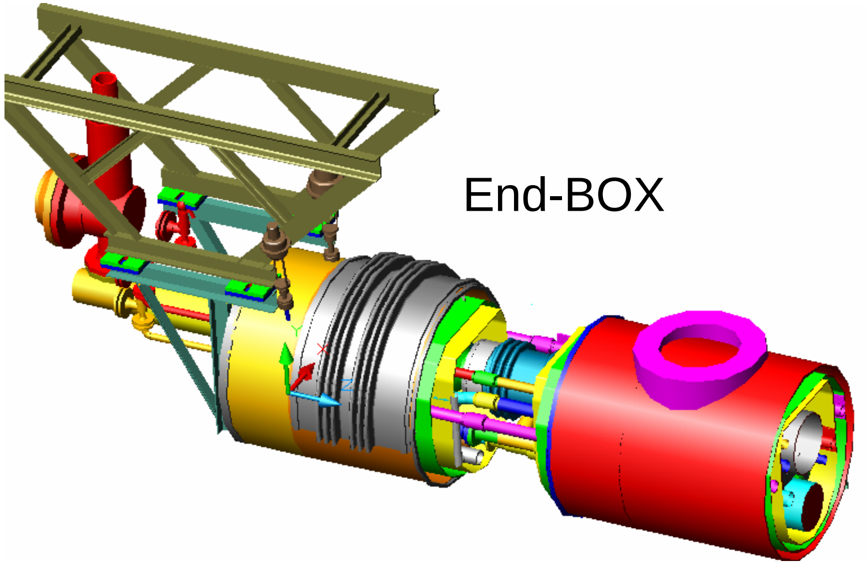
XFEL linac cryogenic components

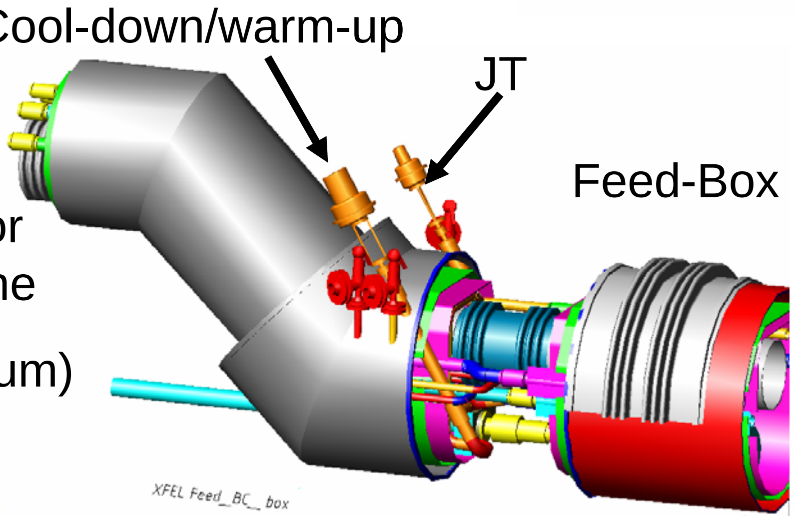
This slide from XFEL_Cryoplant_120506.ppt
by Bernd Petersen

‚regular‘ string connection box

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







Bunch Compressor
Bypass Transferline

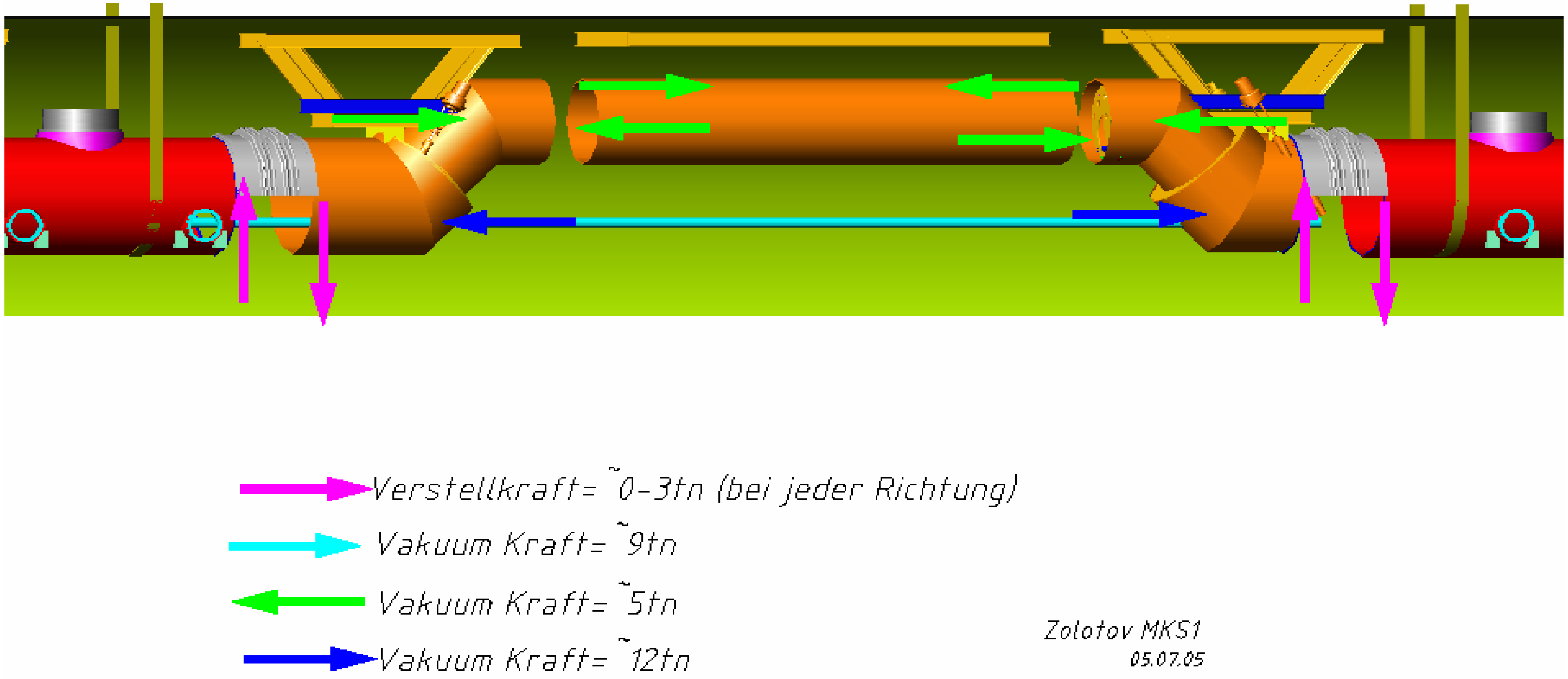
(only 1-phase helium)

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

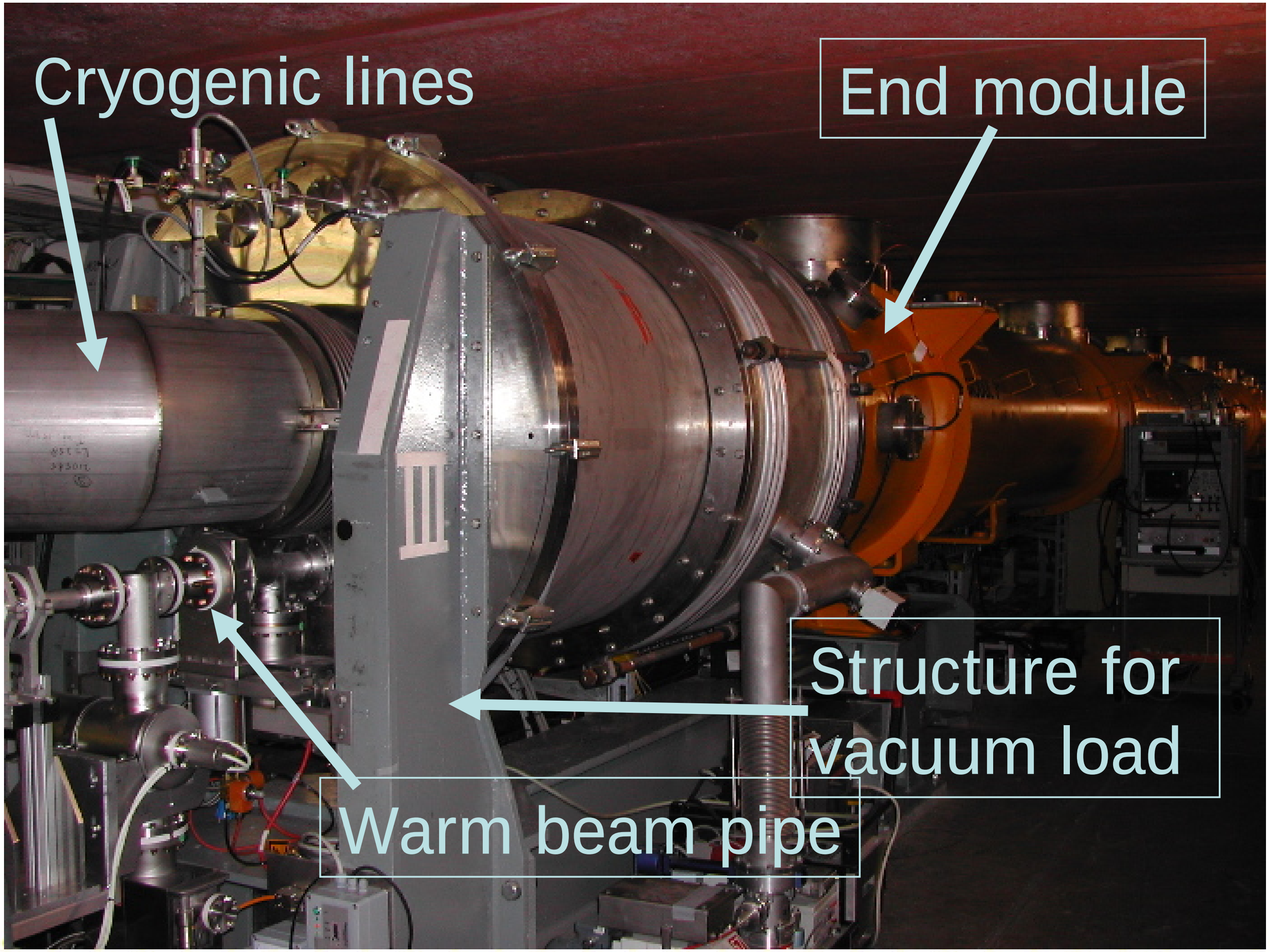
XFEL Bunch-Compressor-Transferlines

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.

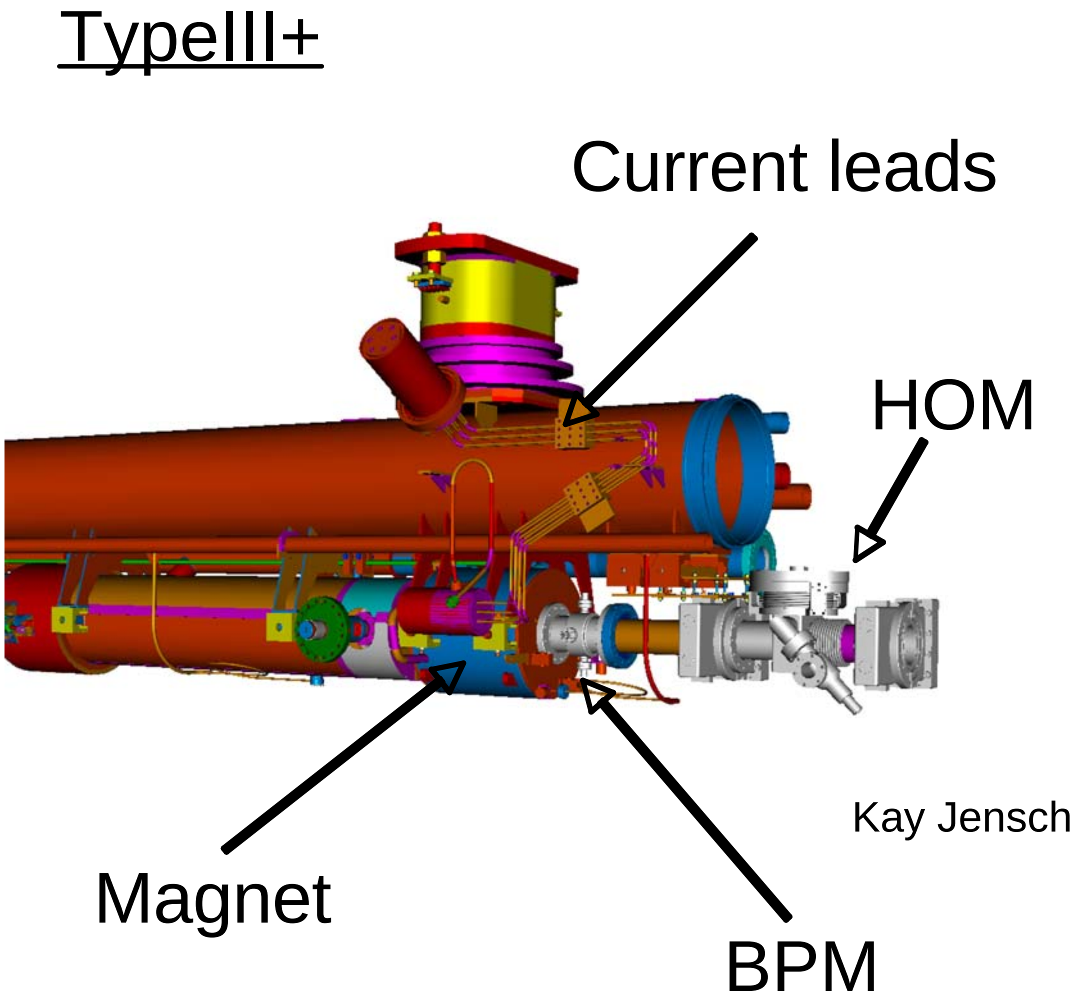


TTF cold-warm transition ~ 2 m



Magnet current leads

- Conductively cooled (no vapor flow)
- Insulated bronze inside a stainless sleeve
- Based on the LHC corrector leads (LHC Project Report 691)

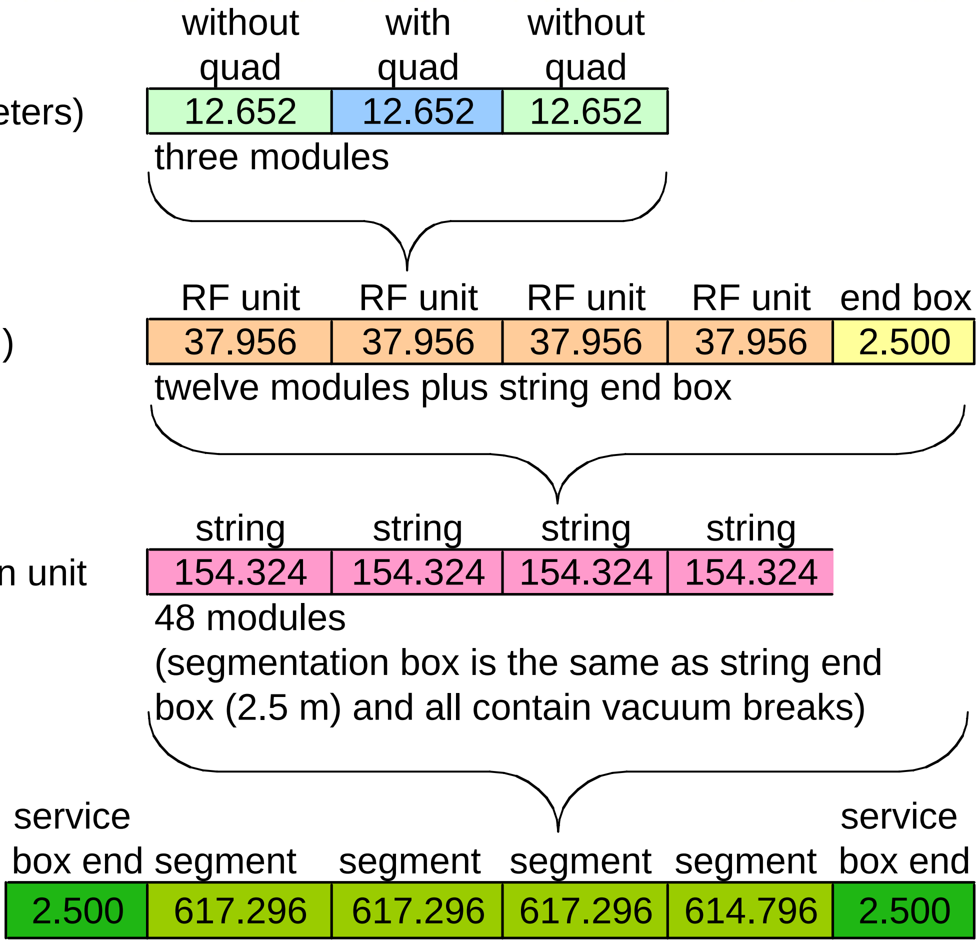


Kay Jensch

Main Linac

- 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
- The following slides describe some of the main linac cryosystem concepts
  - **Will focus on main linac, then follow with about 1 slide each for the other areas**

Main Linac Layout



modules

RF unit (lengths in meters)

without quad	with quad	without quad
12.652	12.652	12.652

three modules

string (vacuum length)

RF unit	RF unit	RF unit	RF unit	end box
37.956	37.956	37.956	37.956	2.500

twelve modules plus string end box

possible segmentation unit

string	string	string	string
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)

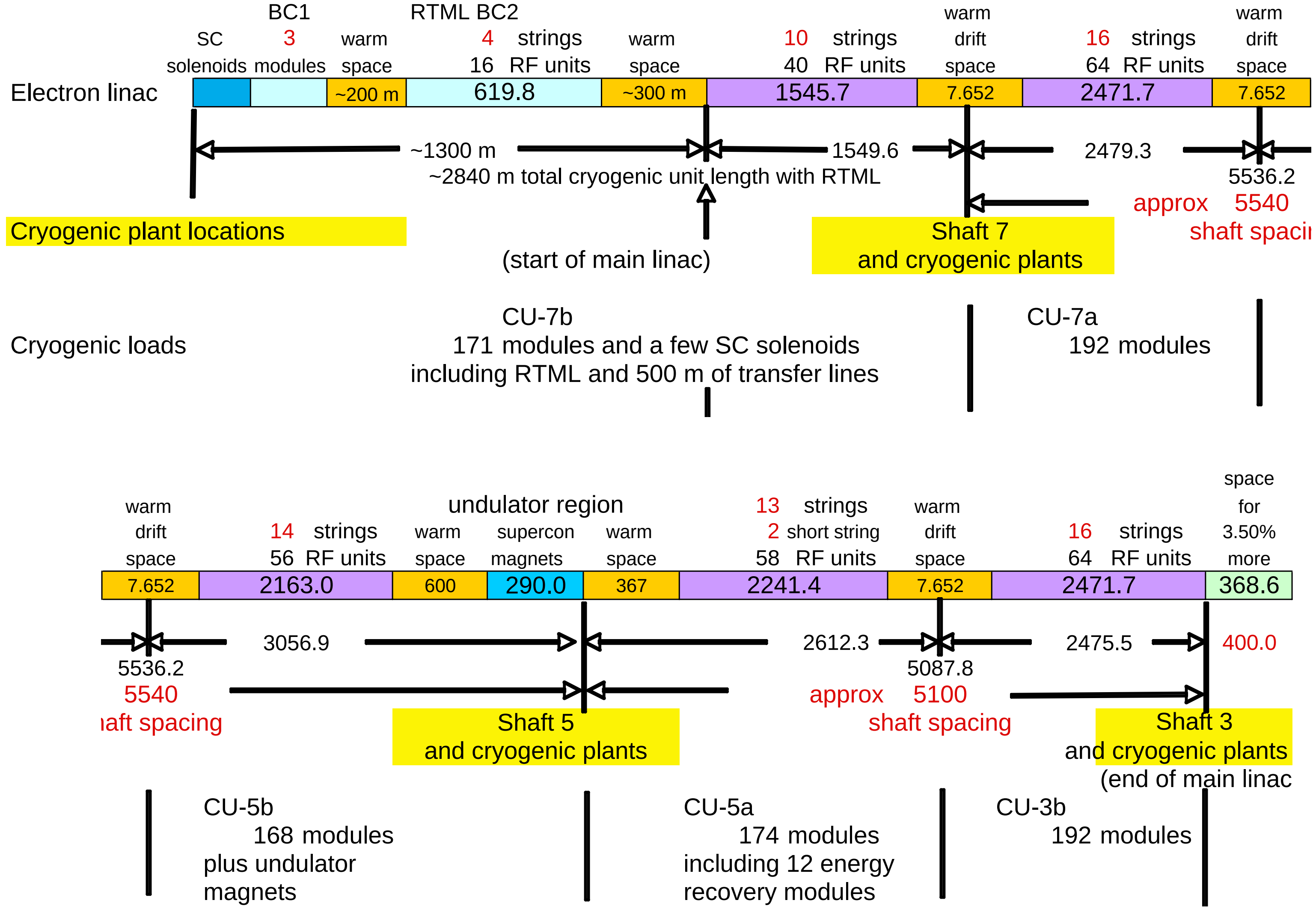
Cryogenic Unit
(16 strings)

service box end	segment	segment	segment	segment	service box end
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



Electron linac

BC1
SC solenoids
3 modules
warm space ~200 m
RTML BC2
4 strings
16 RF units
619.8
warm space ~300 m
10 strings
40 RF units
1545.7
warm drift space 7.652
16 strings
64 RF units
2471.7
warm drift space 7.652

~1300 m
~2840 m total cryogenic unit length with RTML
1549.6
2479.3
5536.2
approx 5540
shaft spaci

Cryogenic plant locations

(start of main linac)

Shaft 7
and cryogenic plants

Cryogenic loads

CU-7b
171 modules and a few SC solenoids
including RTML and 500 m of transfer lines

CU-7a
192 modules

warm drift space 7.652
14 strings
56 RF units
2163.0
undulator region
warm space 600
supercon magnets 290.0
warm space 367
13 strings
2 short string
58 RF units
2241.4
warm drift space 7.652
16 strings
64 RF units
2471.7
space for 3.50% more 368.6

5536.2
5540
aft spacing
3056.9
2612.3
5087.8
approx 5100
shaft spacing
2475.5
400.0

Shaft 5
and cryogenic plants

Shaft 3
and cryogenic plants
(end of main linac

CU-5b
168 modules
plus undulator
magnets

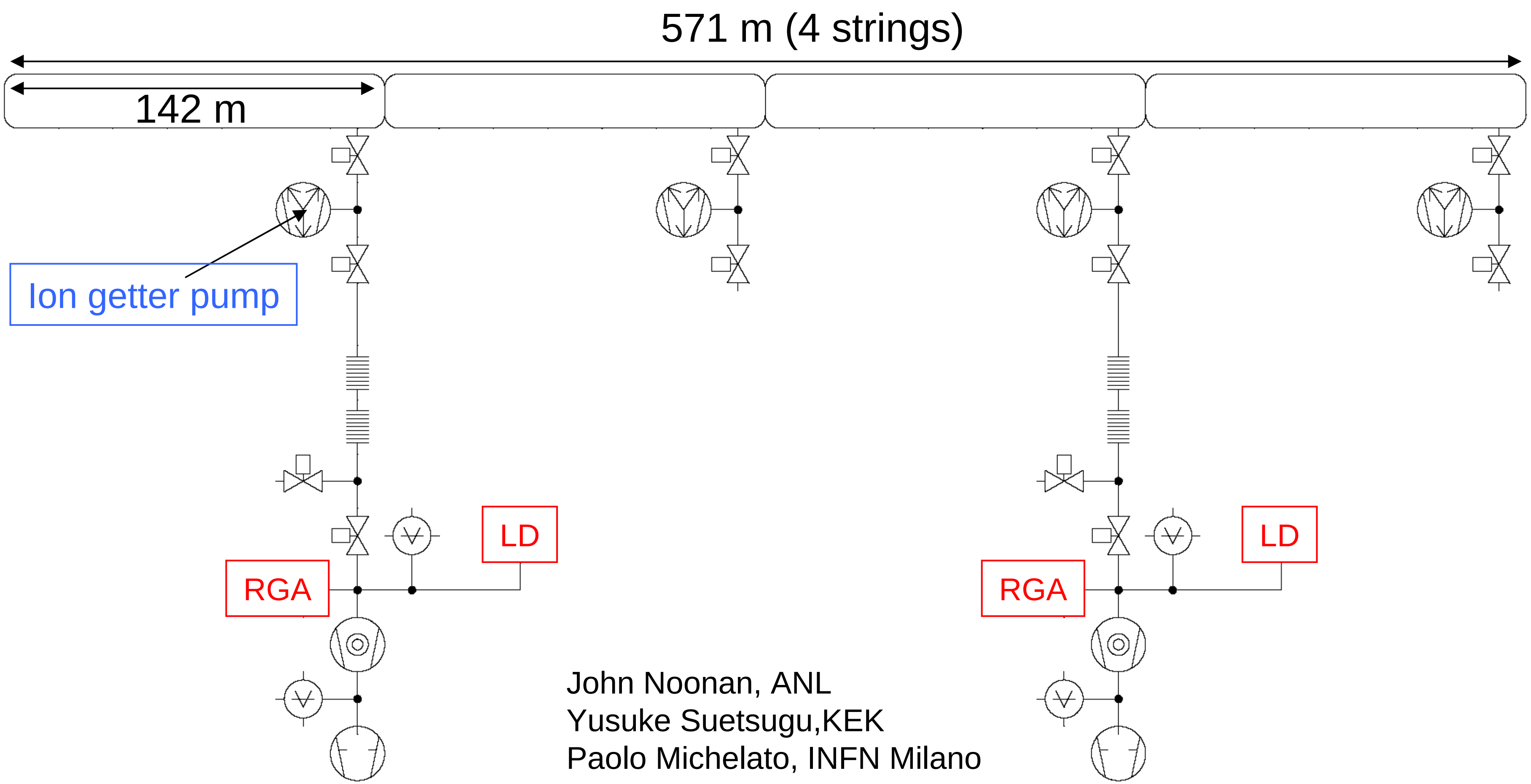
CU-5a
174 modules
including 12 energy
recovery modules

CU-3b
192 modules

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

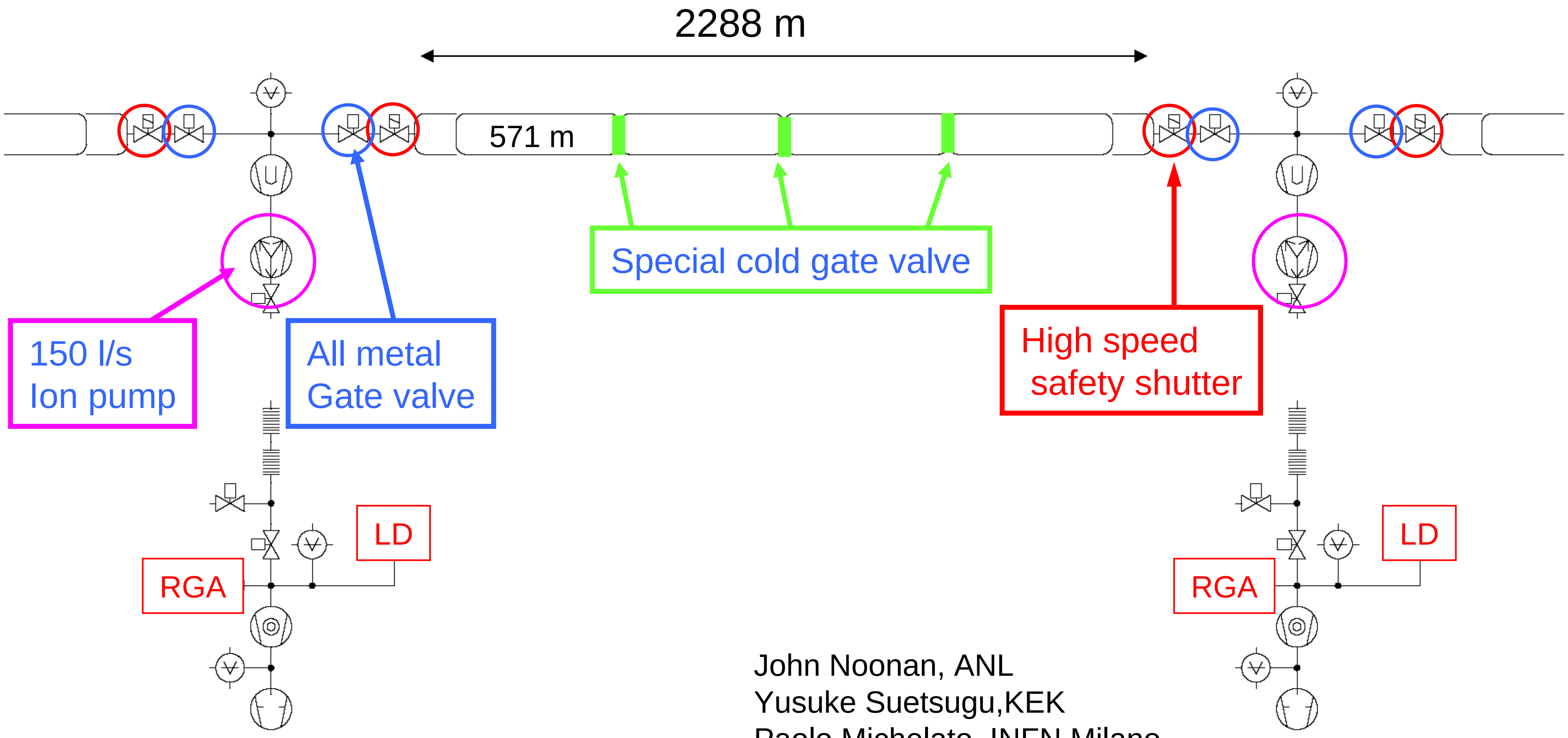
Beam line vacuum system 1/2



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.

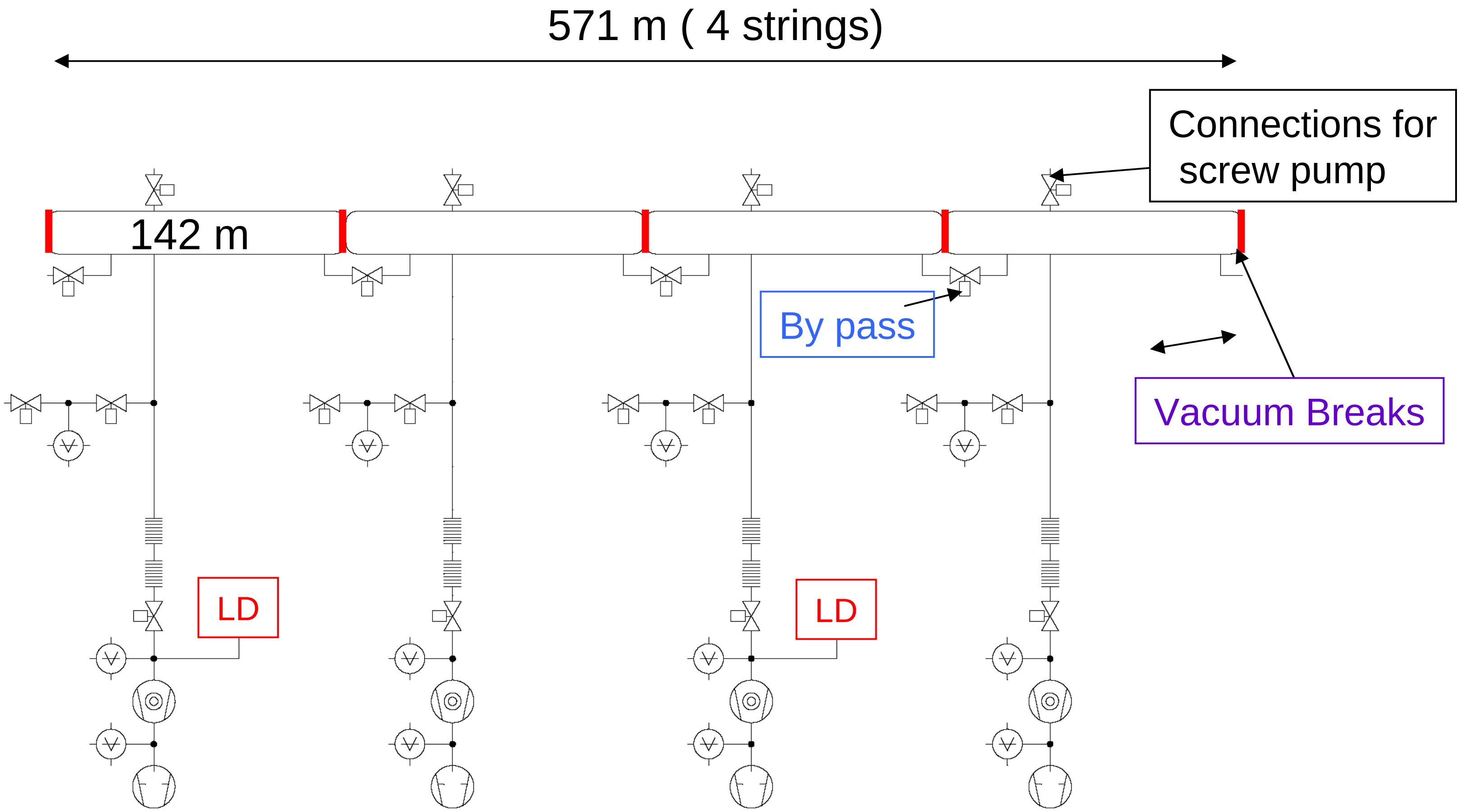
Beam line vacuum system 2/2



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

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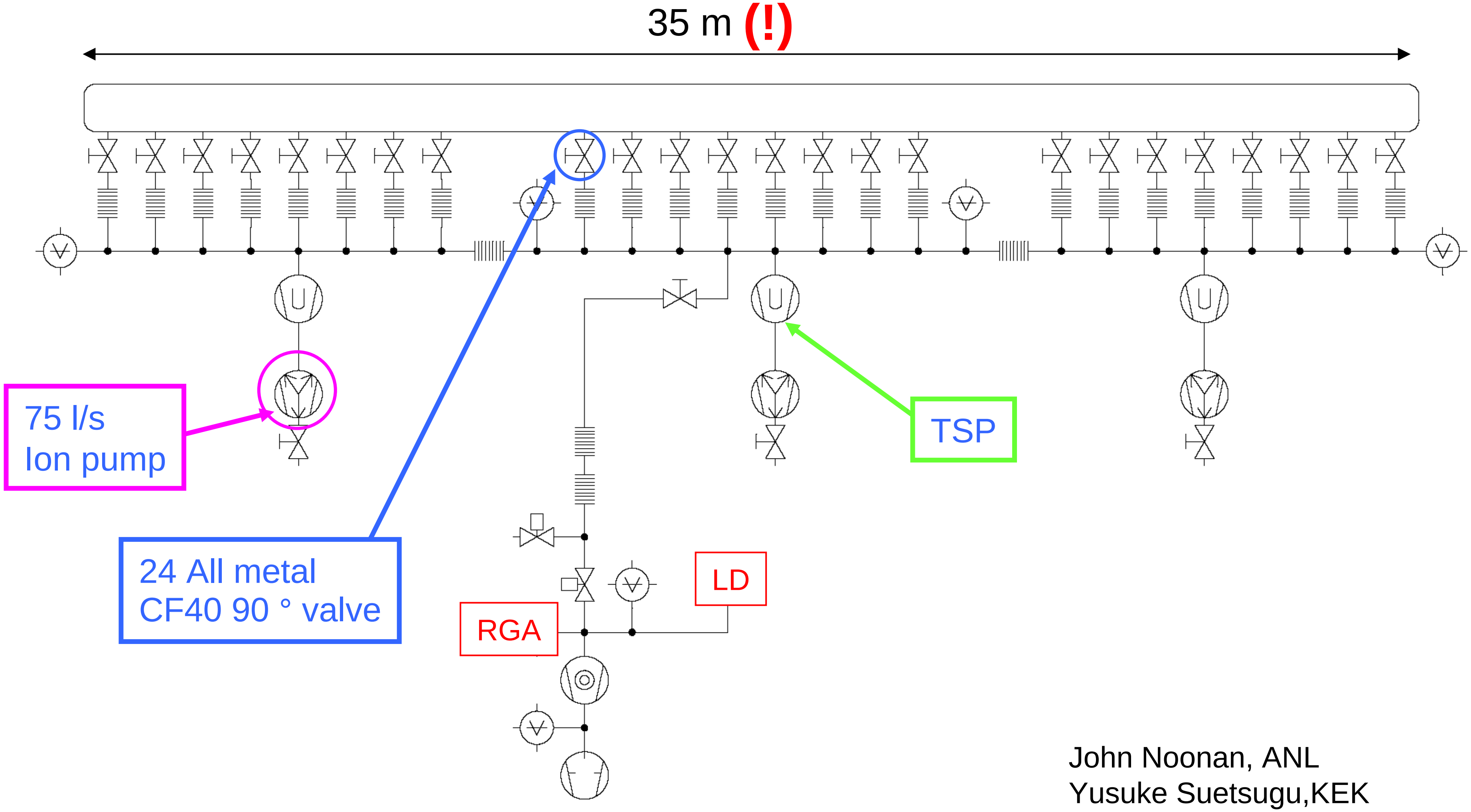
Paolo Michelato, INFN Milano

Coupler vacuum system



35 m **(!)**

75 l/s
Ion pump

24 All metal
CF40 90 ° valve

TSP

RGA

LD

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

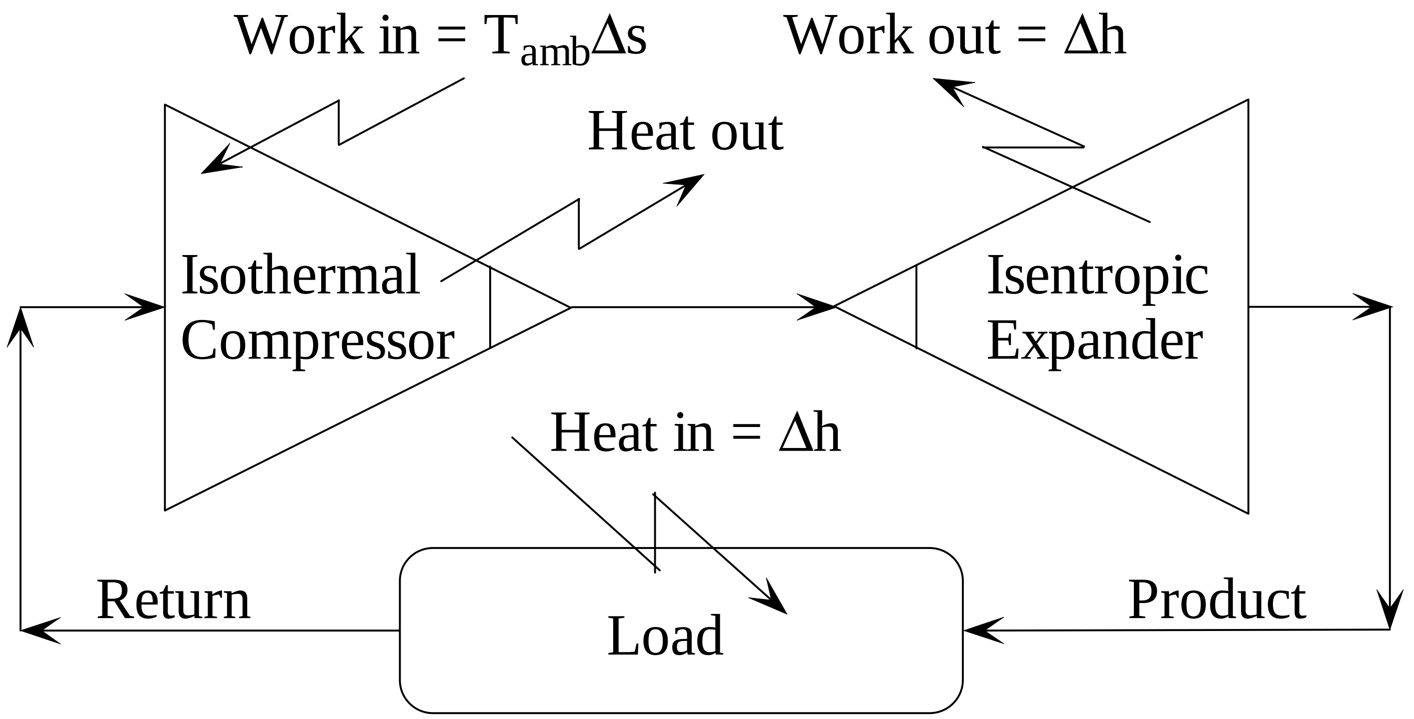
Module predicted heat loads -- 5K

	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 als
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 als
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

Ideal helium process



Net ideal work in = $T_{amb}\Delta s - \Delta h$

(in dimension of energy per unit mass)

Isothermal heat absorption

- Net ideal work (energy per unit mass of working fluid) into the system is $T_{amb}\Delta s - \Delta h$
- For a refrigerator with the heat load absorbed by evaporation at constant liquid temperature, T_{liq}, $\Delta h = T_{liq}\,\Delta s$
- Thus, the ratio of applied work to heat absorbed is $(T_{amb}\,\Delta s - \Delta h)/\,\Delta h = T_{amb}/T_{liq} - 1$
- For low temperatures this is approximately the ratio of absolute temperatures, T_{amb}/T_{l}

Power required for a non-isothermal load

- Use

QuickTime™ and a
Graphics decompressor
are needed to see this picture.

- Where P is the ideal room-temperature power required to remove a non-isothermal heat load
- I will show the use of this later in calculating the ILC cryogenic system power

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**

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.

Cryomodule sketch from TDR

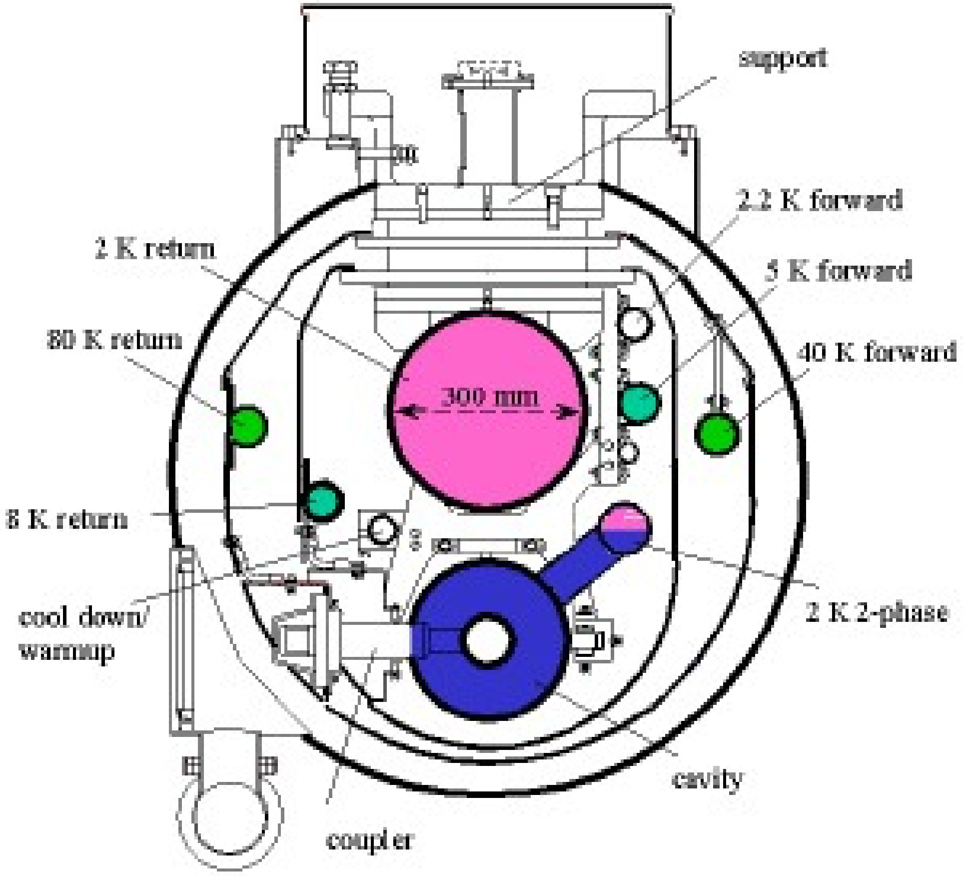


Figure 3.2.11: *Cross section of cryomodule.*

Pipe size summary from Dec 05

Pipe function	BCD designation	TTF inner diameter (mm)	XFEL plan inner diameter (mm)	ILC BCD proposed minimum (mm)
2.2 K subcooled supply	A	45.2	45.2	60
Major return header, structural supp't	B	288	288	288
5 K shield and intercept supply	C	57.5	71	70
8 K shield and intercept return	D	50.0	71	70
40 – 50 K shield supply	E	57.5	71	100
75 - 80 K shield return	F	50.0	71	100
2-phase pipe		72.1	72.1	72.1 (review)
Helium vessel to 2-phase pipe cross-connect		54.9	54.9	54.9

Pressure drop design goals -- 1

- 2 K supply (line A) -- delta-P = 0.1 bar max
  - **Supply to JT valve so pressure drop not a major issue. Dropping pressure through valve anyway.**
    - Consider 4.5 K filling
    - Allow 0.1 bar max for liquid supply during fill
    - Assume flow same as with full 2 K load
- “300 mm” tube (line B) -- dP = 3 mbar max
  - **Tube size is essentially fixed, taken as a parameter restricting cryo unit length**
  - **Taking 3 mbar ==> 33 mK (2.000 K to 2.033 K range over cryogenic unit)**

Pressure drop design goals -- 2

- 5 K - 8 K thermal shield (lines C, D) -- 0.2 bar dP
  - **Operating between 5 bar and 4.0 - 4.5 bar**
    - Pressure and pressure range are somewhat arbitrary choices right now!
    - Must be integrated with plant cycle (true for all flow loops)
  - **Need >50% of dP in valve for control**
    - So aim for 0.2 bar delta-P or less
- 40 K - 80 K thermal shield (lines E, F) -- 1.0 bar dP
  - **Operating between 16 bar and 14 bar**
    - Again, must be integrated with plant cycle (true for all flow loops)
    - This is conservatively low pressure and large delta-P
  - **Want >50% of delta-P in valve for control**
    - So aim for 1 bar delta-P or less

1.2 bar, 2.4 K supply (A)

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

- Goal = 0.1 bar delta-P max
- Early estimate (above) is dP = 0.03 bar over 3 km
  - **(above table by Michael Geynisman, Fermilab)**
- Flow is now estimated at 190 gr/sec, length at 2.5 km ==> 0.04 bar
- 60 mm is very good (45 mm is marginally small)

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)**

5 - 8 K, 5 bar, thermal shield (C, D)

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

- Goal = 0.2 bar delta-P
- Early dP estimate = 0.43 bar over 3 km, but 230 gr/sec is higher flow rate than currently estimated
  - **(above table by Michael Geynisman, Fermilab)**
- **150 gr/sec over 2.5 km scales to 0.15 bar -- OK**
- 70 mm is OK (50 mm would be too small)

40-80 K, 16 bar, thermal shield (E, F)

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

- Goal = 1.0 bar delta-P max
- Early estim. = 2.78 bar dP over 3 km, used 250 gr/sec flow rate
  - **(above table by Michael Geynisman, Fermilab)**
- Currently estimate 225 gr/sec, 2.5 km. Scales to 1.88 bar pressure drop
- 70 mm tube not large enough (want 1 bar pipe dP)
- 100 mm tube ==> pressure drop = 0.45 bar -- very good
- 80 mm tube ==> pressure drop = 1.10 bar -- marginal but OK
- Increase forward pipe (not shield) only? Shield increase is more effective. Prefer to keep both aluminum extrusions same size. **Make all shield pipes 80 mm would be significant help, probably workable.**

Pipe size summary

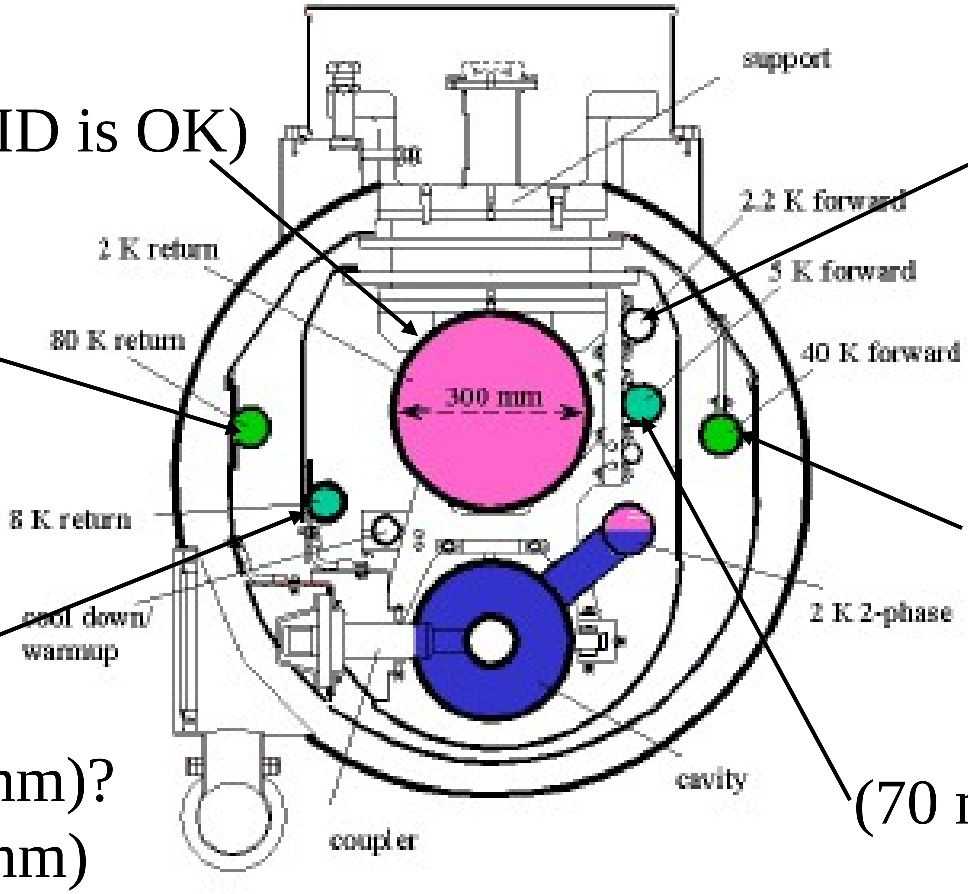


Figure 3.2.11: *Cross section of cryomodule.*

300 mm ID is OK)

(60 mm)

(Increase
diameter
to 80 mm)

(Increase
diameter
to 80 mm)

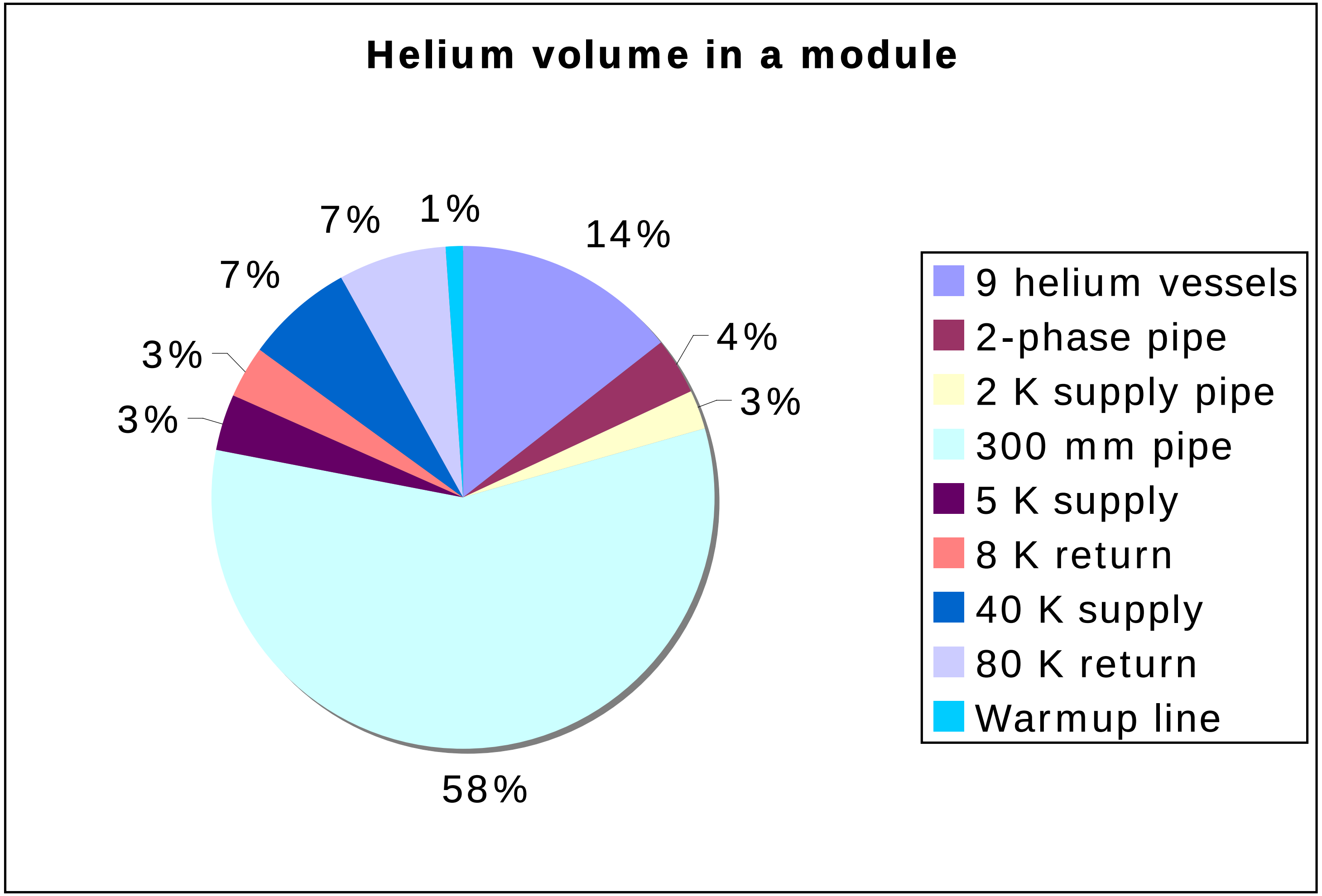
Keep the
same size
as 80 K (80 mm)?
(At least 70 mm)

(70 mm)

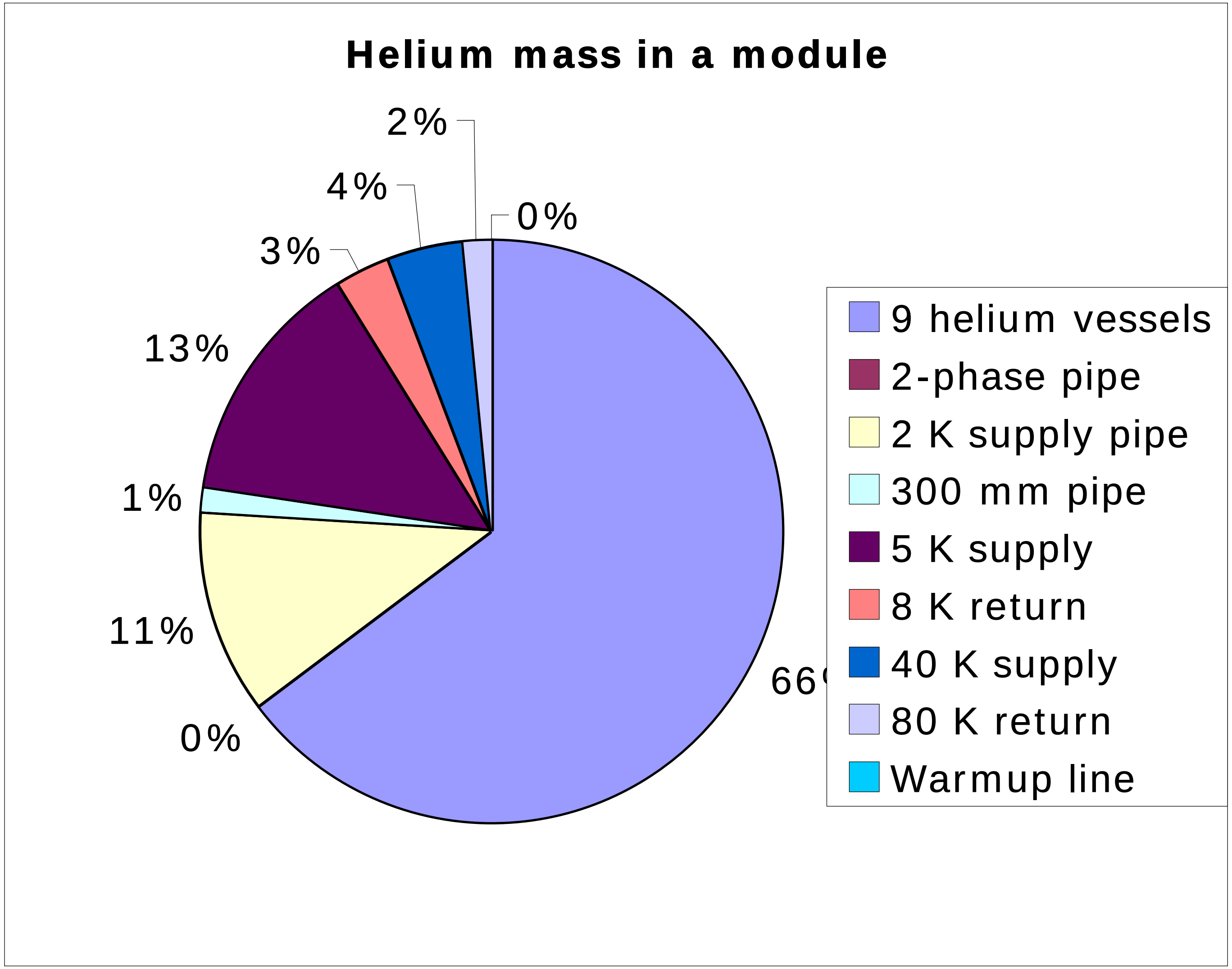
Pipe size summary now (Jan 07)

Pipe function	BCD name	TTF inner diameter (mm)	XFEL plan inner diameter (mm)	**ILC 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	57.5	71	**70**	
8 K shield and intercept return	D	50.0	71	**80**	0.20 bar (C+D)
40 – 50 K shield supply	E	57.5	71	**80**	
75 - 80 K shield return	F	50.0	71	**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

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.

RTML

- Included in Main Linac layout as a cryogenic unit cooled from pts 6 and 7
- Cost of refrigeration scaled like 2 K heat loads

Note on dividing costs between RTML and Main Linac

Heat loads for transfer lines like module static, so 15% of module

3 modules in BC1 plus 3*15 modules in BC2

500 m of transfer lines = 75 m of modules = 6 modules

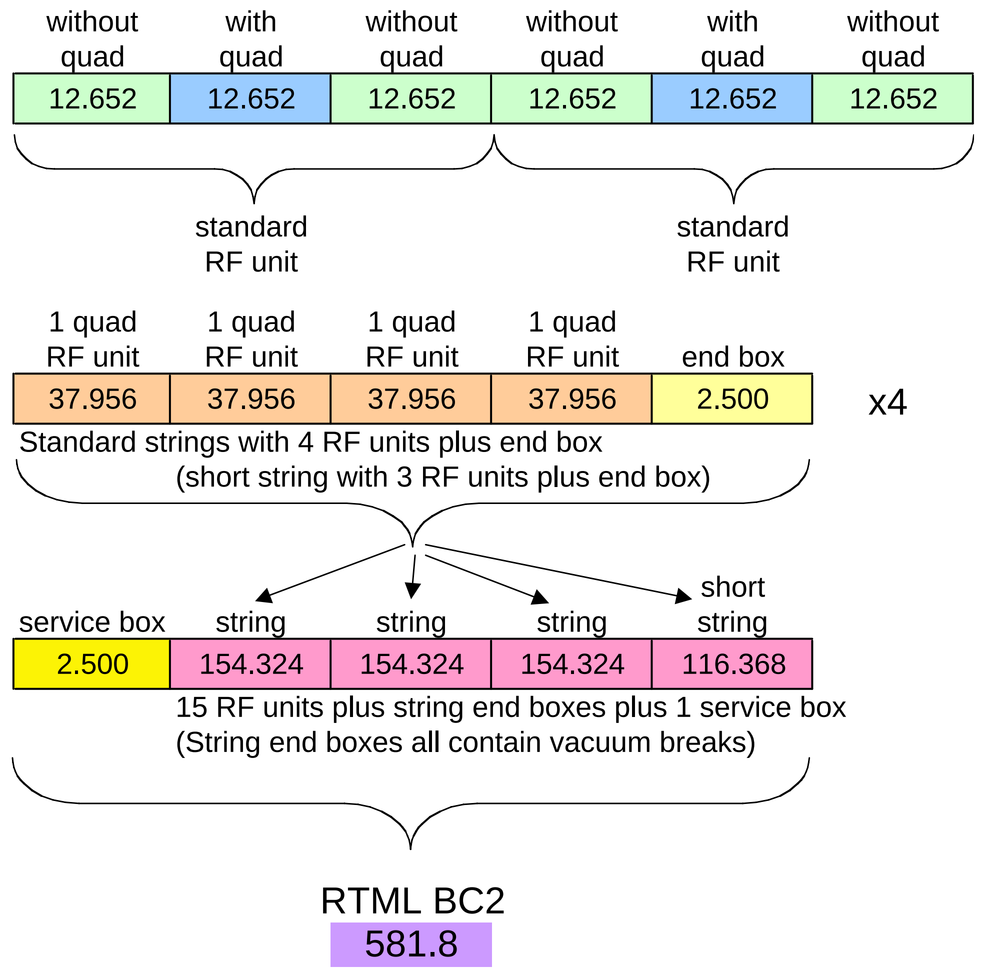
Count SC solenoids as one module for equivalent heat

RTML total modules = 55 modules equivalent heat load

Fraction of ML total = 0.065

RTML BC2 follows main linac pattern

RTML (updated to show standard RF units, one quad in three modules)



modules

RF units (module lengths in meters)

without quad	with quad	without quad	without quad	with quad	without quad
12.652	12.652	12.652	12.652	12.652	12.652

standard RF unit

standard RF unit

strings

1 quad RF unit	1 quad RF unit	1 quad RF unit	1 quad RF unit	end box
37.956	37.956	37.956	37.956	2.500

x4

Standard strings with 4 RF units plus end box
(short string with 3 RF units plus end box)

BC2 modules in RTML

service box	string	string	string	short string
2.500	154.324	154.324	154.324	116.368

15 RF units plus string end boxes plus 1 service box
(String end boxes all contain vacuum breaks)

RTML BC2
581.8

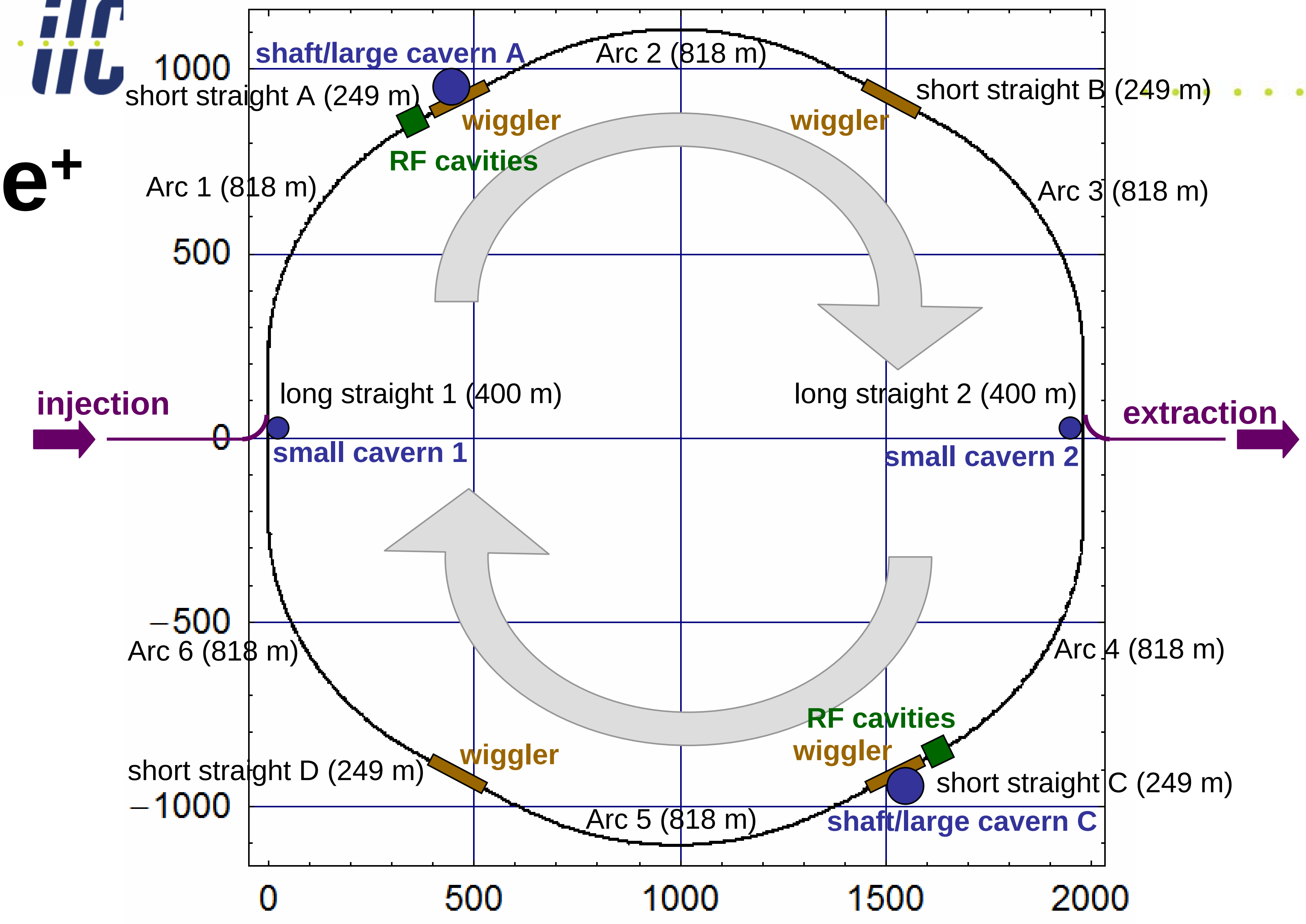
Damping ring cryogenics

	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 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 4.5 kW at 4.5 K.

e+



A. Wolski, 9 Nov 2006

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		372.9			
String	12 modules	4,474.5	0.1		13.42
Cryogenic unit	16 strings	67,862.5	1.1	0.1	203.59
ILC main linacs	2x5 cryo units	678,998.2	11.3	0.9	2036.99

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	4.35	43.52	3.39	33.91
Sources	2.00	0.59	1.18	0.46	0.92
Damping Rings	2.00	1.26	2.52	0.88	1.76
BDS	1.00	0.41	0.41	0.33	0.33
TOTAL			**47.63**		**36.92**

- 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

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)

Cryogenic system design status

- Fairly complete accounting of cold devices with heat load estimates and locations
  - **Some 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 equiv.**
- 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**

Decisions still pending

- Features for managing emergency venting of helium need development effort
  - **Large vents and/or fast-closing vacuum valves are required for preventing overpressure on cavity**
  - **Large gas line in tunnel?**
  - **Spacing of vacuum breaks**
- Helium inventory management schemes need more thought
- Consider ways to group compressors, cooling towers, and helium storage so as to minimize surface impact
  - **New ILC layout with central sources and damping rings may provide significant opportunities for grouping at least of compressors, which are major power and water users and have the most visible surface impact.**

Possibility for Cost Optimization

- Cryomodule / cryogenic system cost trade-off studies
  - **Additional 1 W at 2 K per module ==> additional capital cost to the cryogenic system of $4300 to $8500 per module (depending on whether we scale plant costs or scale the whole cryogenic system). (5 K heat and 80 K heat are much cheaper to remove than 2 K.)**
  - **Additional 1 W at 2 K per module ==> additional installed power of 3.2 MW for ILC or $1100 per year per module operating costs.**
  - **Low cryo costs relative to module costs suggest that an optimum ILC system cost might involve relaxing some module features for ease of fabrication, even at the expense of a few extra watts of static heat load per module.**
    - For example, significant simplification of thermal shields, MLI systems, and thermal strapping systems

Towards the EDR

- 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 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)
- Consider impact of cool-down, warm-up and off-design operations
- Evaluate requirements for loss-of-vacuum venting
- Contract with industry for a main linac cryogenic plant conceptual design and cost study (which will also feed back to system design)