ILC Main Linac Cooling-Water System

Cost Reduction Studies

- Interim Report -

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ILC GDE Meeting

5 June 2008, JINR (Dubna)

Priority of study on process cooling water

Proportion of process cooling water in total infrastructure (excl. survey)

Schematic Understanding of ML Cooling System & Costs

Focus on
- Shaft #7 Area -

Geometry of Facility

Cooling Tower building ~700 m2

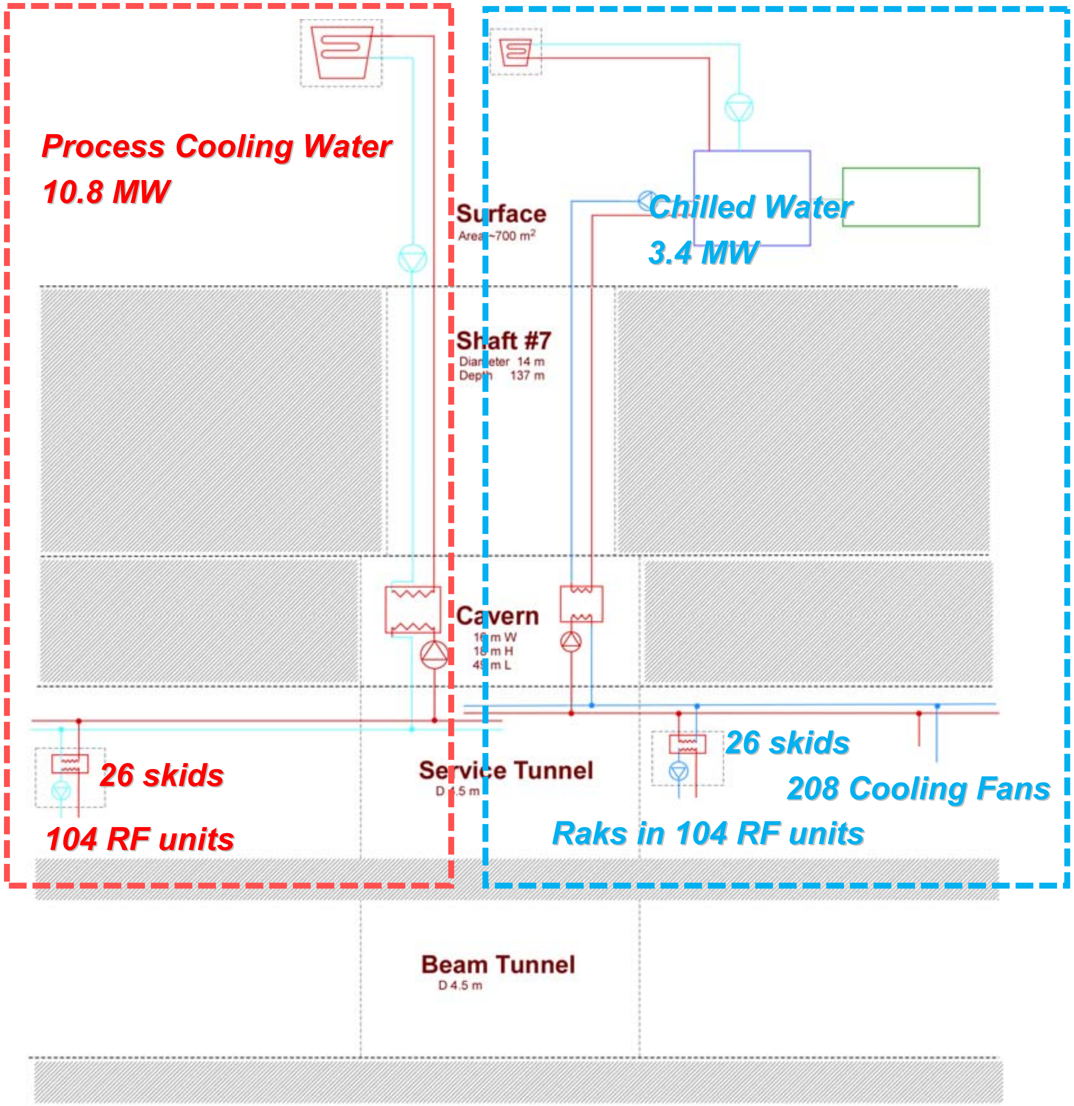
Shaft	14 mϕ, 137 m (450 ft) depth
Cavern	16 m(W), 18 m(H), 49 m(L)
Tunnel	4.5 mϕ, ~4030 m (1550 + 2480)

RF Unit Heat Loads

To Low-Conductivity Water	104 kW
To Chilled Water	21.2 kW
Rack	11.5 kW
Service Tunnel Air	9.7 kW
To Beam Tunnel Air	5.9 kW

Shaft #7 Total Heat Loads

Number of RF units	104
Low-Conductivity Water	10.8 MW
Chilled Water	2.2 MW



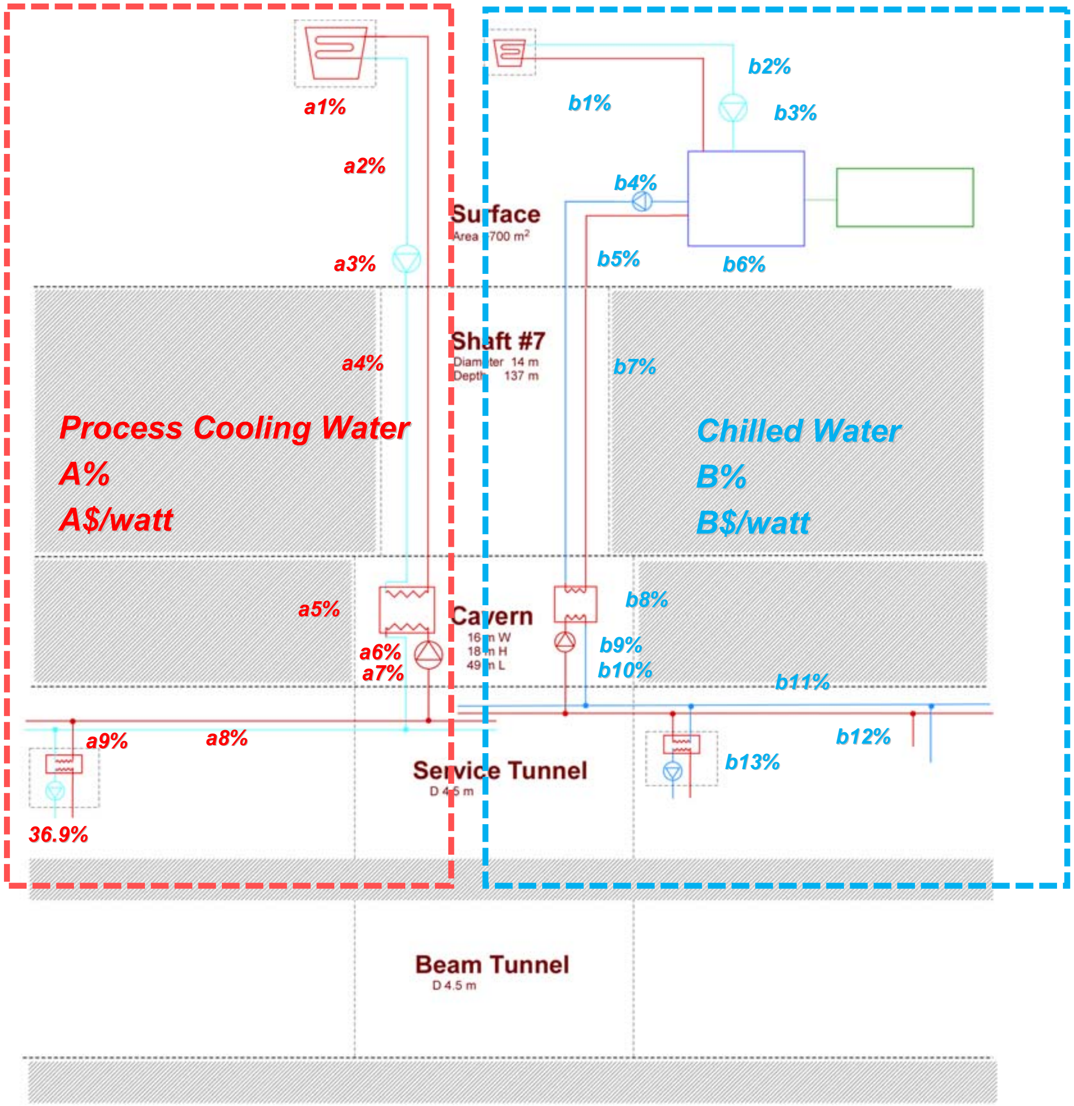
Cost Profile

ML cooling system cost is ~half of total area

Process Cooling Water piping cost is expensive,

including high percentage of LCW skids system ()

Low cost performance of Chilled water system



Targets of study

1. Increase of ΔT (11℃→20℃)
2. Elimination of chilled water

Increase of ∆T from 11℃ to 20℃

This decreases water flow,

- small pipe size,

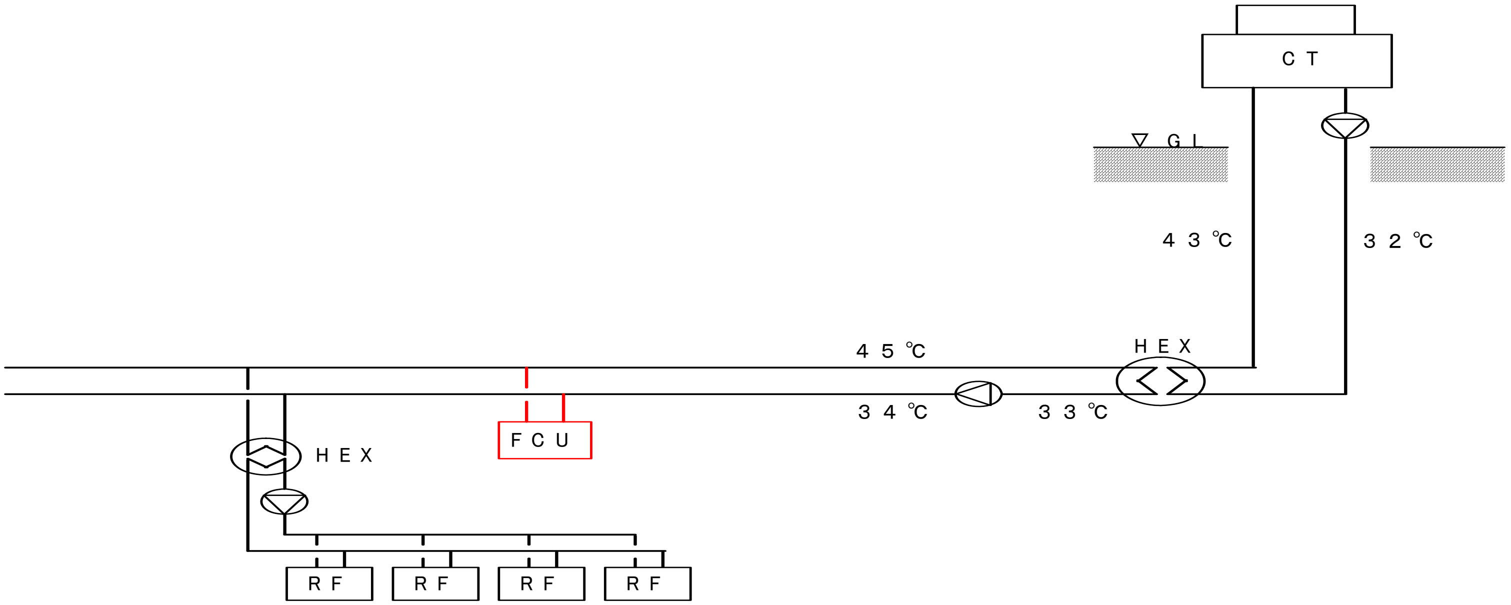
Increase return pipe temperature

Very preliminary results

- Cost reduction in approx. 7%

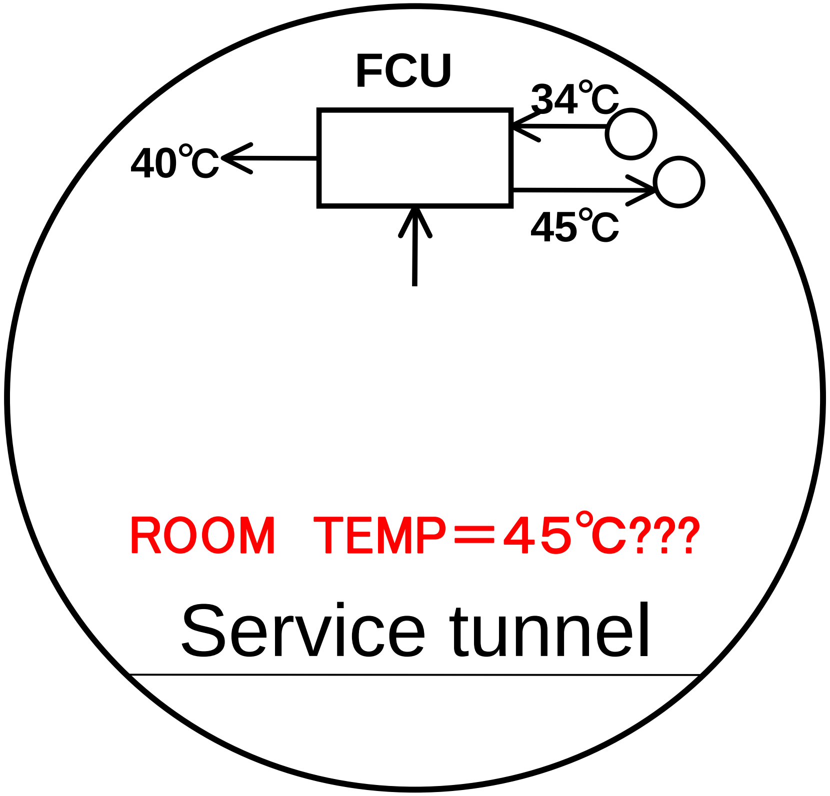
Elimination of Chilled Water

- Simplify the system and reduces the cost
- Affects cooling of the service tunnel



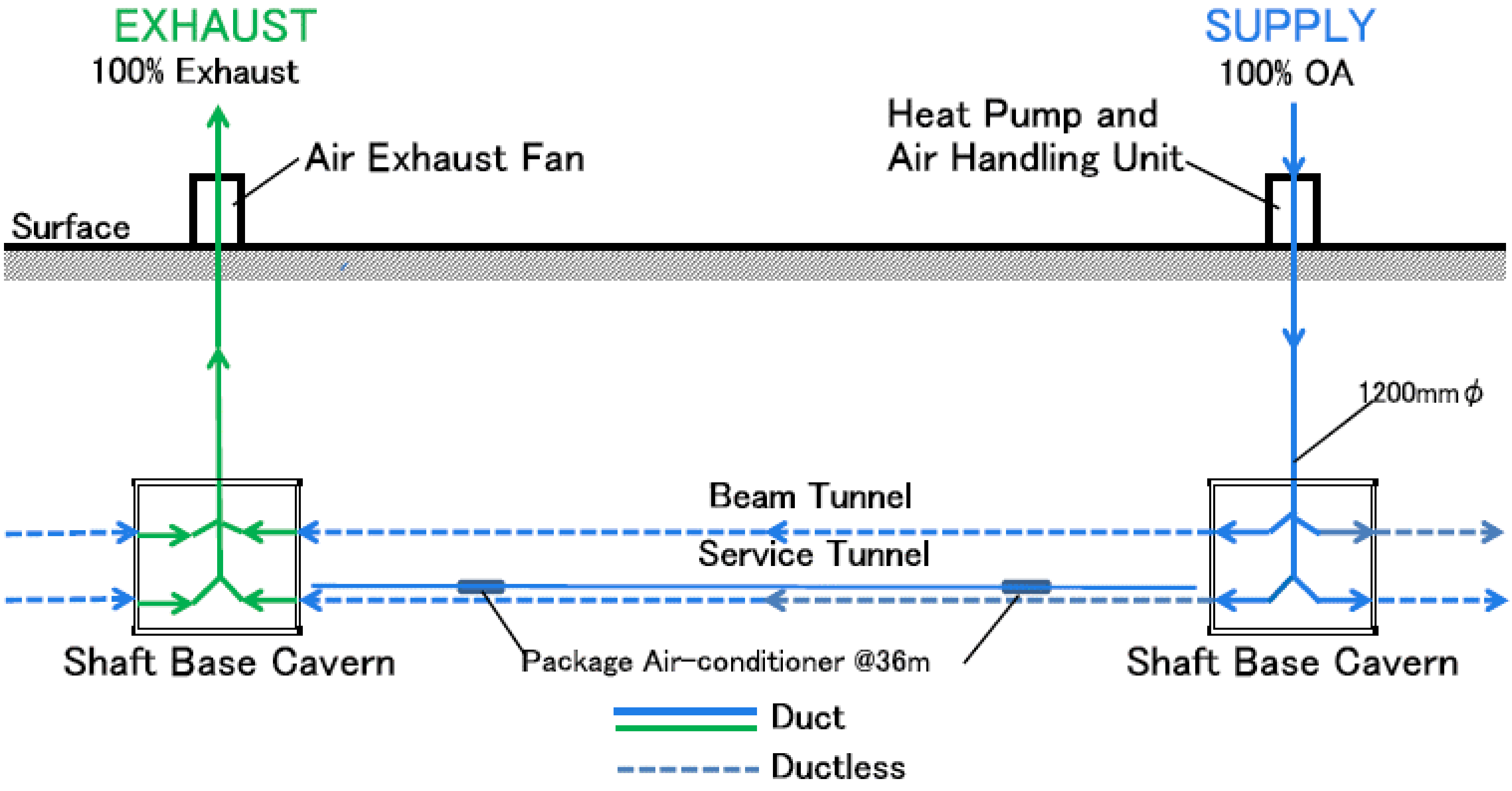
Expected circumstance

- Without chilled water to FCU, temperature of the service tunnel might rise to 45℃ -> discussed later



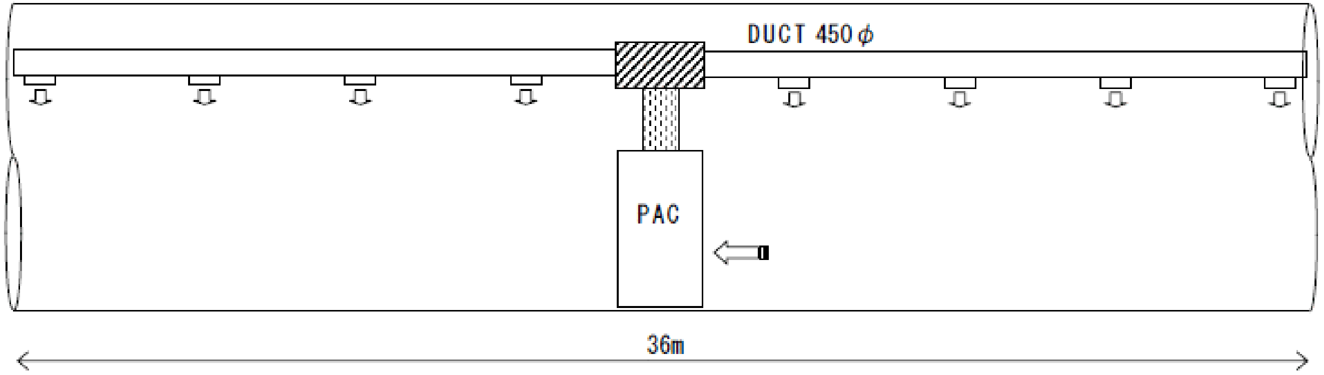
Alternative HVAC scheme for tunnels

- supply & exhaust @ every other shafts



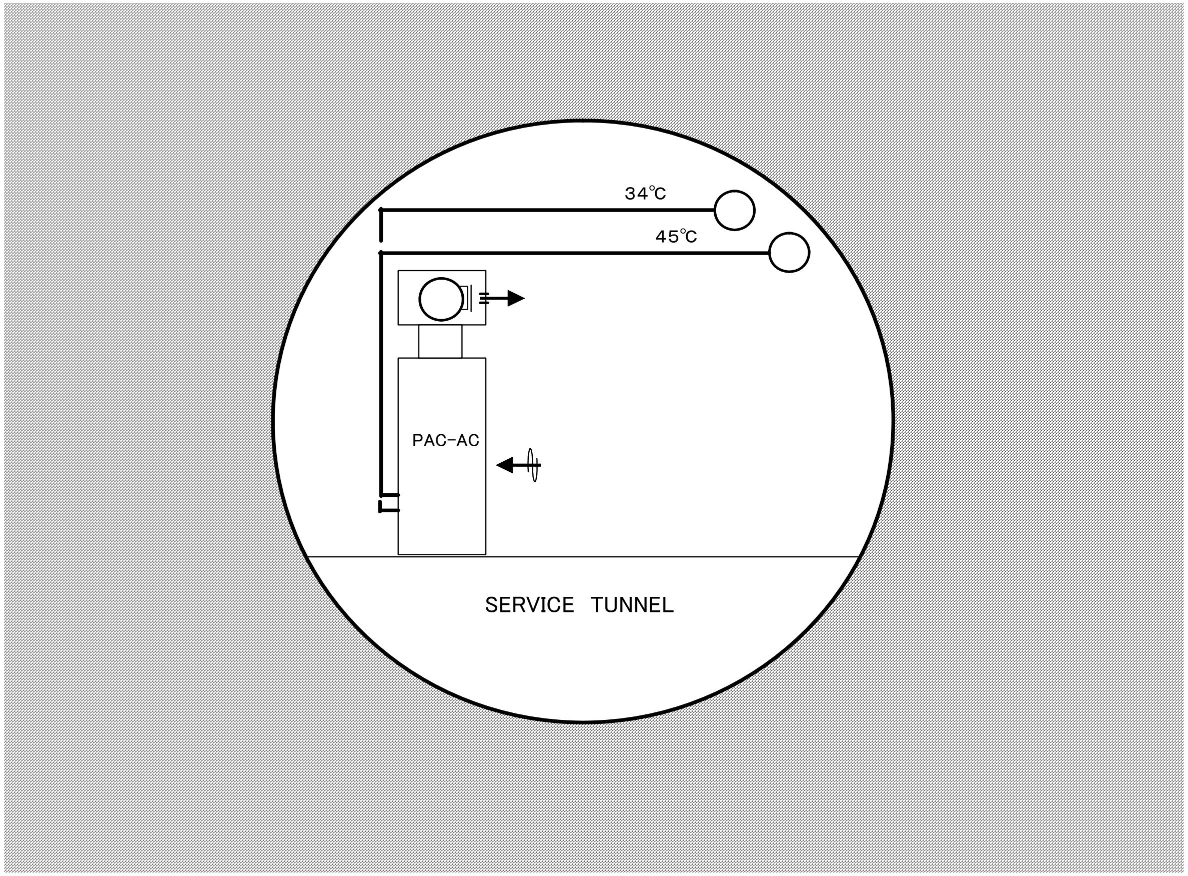
Alternative HVAC system for service tunnel

- Provision of package air-conditioner to replace fan coil unit @ 36 m



- Service tunnel temperature : 25℃～28℃
- Space for package units must be secured
- Further cost study must be done

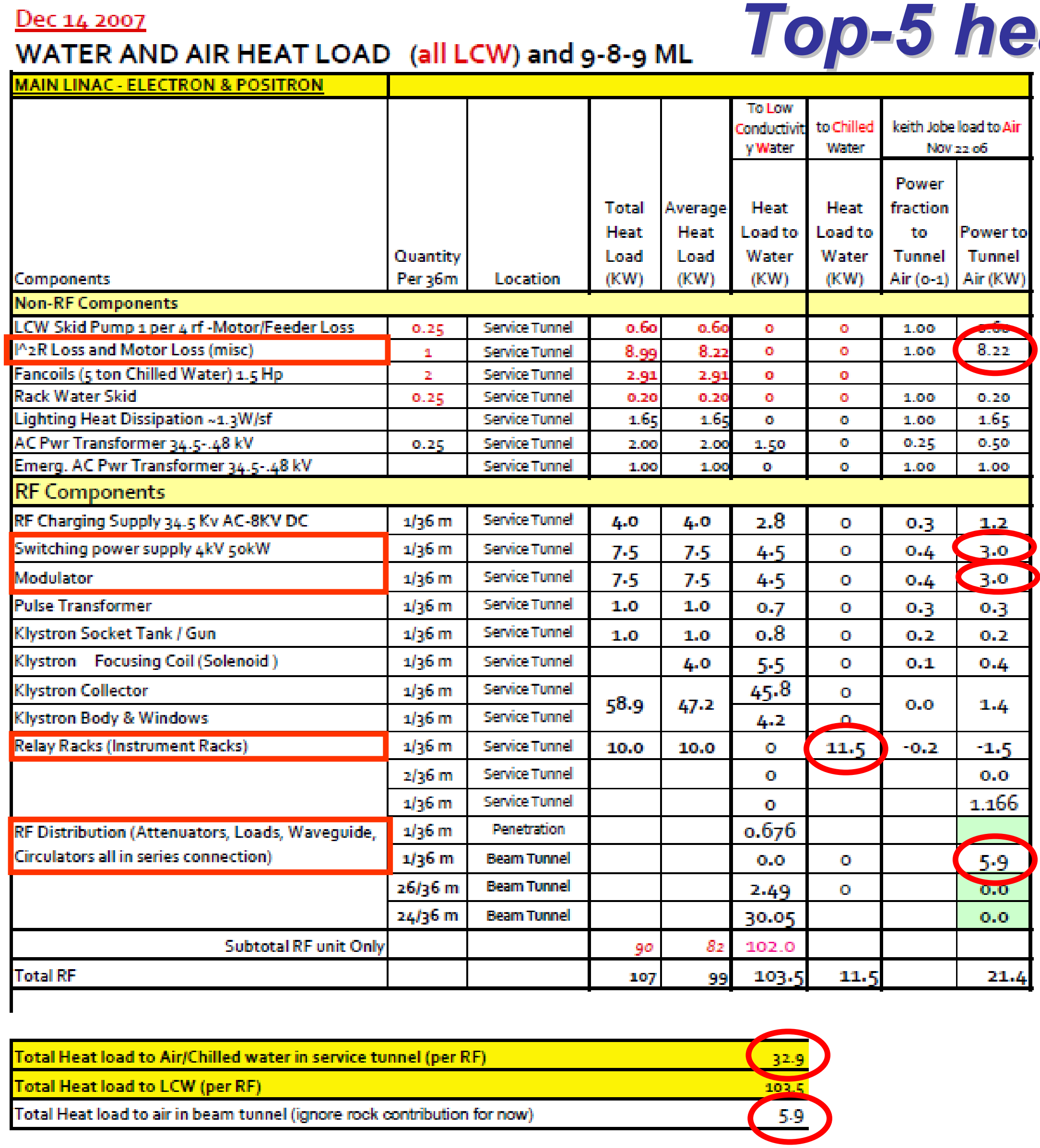
Size and space of package unit



Heat loads to Air/ChW

We had an RDR design and proposed alternative but coming back to the criteria for heat loads ….

Top-5 heat loads to Air/ChW

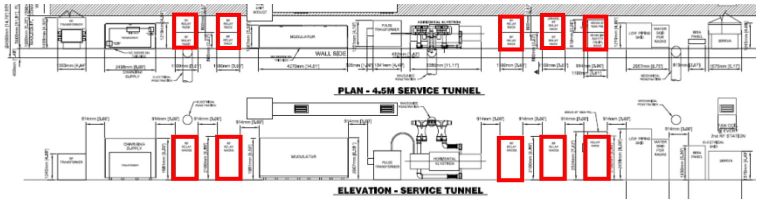


Dec 14 2007

WATER AND AIR HEAT LOAD (all LCW) and 9-8-9 ML

MAIN LINAC - ELECTRON & POSITRON					To Low Conductivity Water	to Chilled Water	keith Jobe load to Air Nov 22 06	
Components	Quantity Per 36m	Location	Total Heat Load (KW)	Average Heat Load (KW)	Heat Load to Water (KW)	Heat Load to Water (KW)	Power fraction to Tunnel Air (0-1)	Power to Tunnel Air (KW)
Non-RF Components								
LCW Skid Pump 1 per 4 rf -Motor/Feeder Loss	0.25	Service Tunnel	0.60	0.60	0	0	1.00	0.60
I^2R Loss and Motor Loss (misc)	1	Service Tunnel	8.99	8.22	0	0	1.00	8.22
Fancoils (5 ton Chilled Water) 1.5 Hp	2	Service Tunnel	2.91	2.91	0	0		
Rack Water Skid	0.25	Service Tunnel	0.20	0.20	0	0	1.00	0.20
Lighting Heat Dissipation ~1.3W/sf		Service Tunnel	1.65	1.65	0	0	1.00	1.65
AC Pwr Transformer 34.5-.48 kV	0.25	Service Tunnel	2.00	2.00	1.50	0	0.25	0.50
Emerg. AC Pwr Transformer 34.5-.48 kV		Service Tunnel	1.00	1.00	0	0	1.00	1.00
RF Components								
RF Charging Supply 34.5 Kv AC-8KV DC	1/36 m	Service Tunnel	4.0	4.0	2.8	0	0.3	1.2
Switching power supply 4kV 50kW	1/36 m	Service Tunnel	7.5	7.5	4.5	0	0.4	3.0
Modulator	1/36 m	Service Tunnel	7.5	7.5	4.5	0	0.4	3.0
Pulse Transformer	1/36 m	Service Tunnel	1.0	1.0	0.7	0	0.3	0.3
Klystron Socket Tank / Gun	1/36 m	Service Tunnel	1.0	1.0	0.8	0	0.2	0.2
Klystron Focusing Coil (Solenoid)	1/36 m	Service Tunnel		4.0	5.5	0	0.1	0.4
Klystron Collector	1/36 m	Service Tunnel	58.9	47.2	45.8	0	0.0	1.4
Klystron Body & Windows	1/36 m	Service Tunnel			4.2	0		
Relay Racks (Instrument Racks)	1/36 m	Service Tunnel	10.0	10.0	0	11.5	-0.2	-1.5
	2/36 m	Service Tunnel			0			0.0
	1/36 m	Service Tunnel			0			1.166
RF Distribution (Attenuators, Loads, Waveguide, Circulators all in series connection)	1/36 m	Penetration			0.676			
	1/36 m	Beam Tunnel			0.0	0		5.9
	26/36 m	Beam Tunnel			2.49	0		0.0
	24/36 m	Beam Tunnel			30.05			0.0
Subtotal RF unit Only			90	82	102.0			
Total RF			107	99	103.5	11.5		21.4

Total Heat load to Air/Chilled water in service tunnel (per RF)	32.9
Total Heat load to LCW (per RF)	103.5
Total Heat load to air in beam tunnel (ignore rock contribution for now)	5.9



1. Racks	11.5 kW
2. I^2R & Motor Loss	8.2 kW
3. Waveguides (B.T.)	5.9 kW
4. Switching P.S.	3.0 kW
5. Modulator	3.0 kW

Total of top 5 = 31.6 kW

….. 82% of Air/Chilled Water Loads

But are these loads real and cannot we reduce?…

Parametric Consideration

To understand heat loads to air, lets see how are heat diffusion and conduction..

Heat Diffusion from Plates

$$q(W/m^2) = U(\theta-\theta_a)$$

U: Heat transfer rate ($W/m^2/K$)

θ: Equipment temperature (C)

θ_a: Ambient temperature (C)

$$U = (R_{se}+R_i)^{-1}$$

R_{se}: Surface heat resistance

R_i : Heat resistance of the material

$$R_{se} = (h_r + h_{cv})^{-1}$$

h_r: HTE by "Radiation"

h_r: HTE by "Convection"

$$h_r = \varepsilon\sigma(T_{se}^{\ 4} - T_a^{\ 4})/(T_{se} - T_a)$$

ε: Efficiency due to the material, ex. 0.30 (stainless steel), 0.94 (cement, cloth)

σ: Stefan-Boltsmann constant, $5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$

T_{se}: Surface temperature (K), T_a: Ambient temperature (K)

$$h_{cv} = \begin{cases} 3.26\Delta\theta^{0.25}((w+0.348)/0.348)^{0.5} & \text{upward-directed surface} \\ 2.28\Delta\theta^{0.25}((w+0.348)/0.348)^{0.5} & \text{doward-directed surface} \\ 2.56\Delta\theta^{0.25}((w+0.348)/0.348)^{0.5} & \text{vertical planes } (\Delta\theta > 10K) \\ (3.61+0.094\Delta\theta)^{0.25}((w+0.348)/0.348)^{0.5} & \text{vertical planes } (\Delta\theta < 10K) \end{cases}$$

$\Delta\theta = | T_{se} - T_a |$

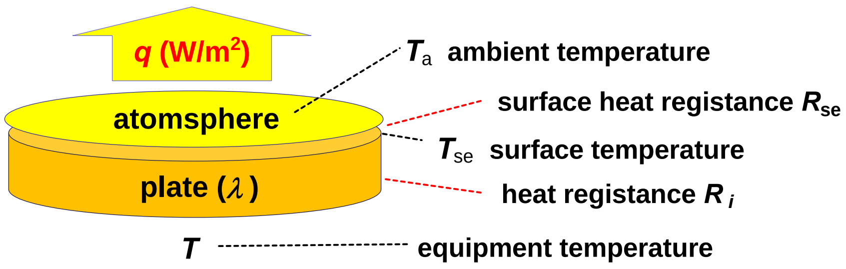
w: Air flow velocity (m/s)

$$R_i = d/\lambda$$

d: Thickness of the material (m)

λ : Thermal conductivity of the material ($Wm^{-1}K^{-1}$)

Heat diffusion by Radiation and Convection



The order of "Surface Heat Resistance"

For T_a (ambient temperature) 29 C
and T_{se} (surface temperature) 34~54 C

(1) Heat Radiation

assume $\varepsilon = 1.0$

$h_r = \varepsilon\sigma(T_{se}^4 - T_a^4) / (T_{se} - T_a) = 6.4 \sim 7.1\ (Wm^{-2}K^{-1})$

(2) Air convection

assume w = 0.45 m/s (27 m/min)

$h_{cv} = 3.26\Delta\theta^{0.25}((w+0.348)/0.348)^{0.5} = 7.4 \sim 11.0\ (Wm^{-2}K^{-1})$ upward-directed surface

$h_{cv} = 2.56\Delta\theta^{0.25}((w+0.348)/0.348)^{0.5} = 5.8 \sim 8.7\ (Wm^{-2}K^{-1})$ vertical planes ($\Delta\theta$ >10 K)

(3) Overall heat diffusion from equipment surfaces

assume $\varepsilon = 1.0$ and w = 0.45 m/s (27 m/min)

$h = 12 \sim 18\ W/m^2/K$ (for $\Delta T = 5 \sim 25$ deg)

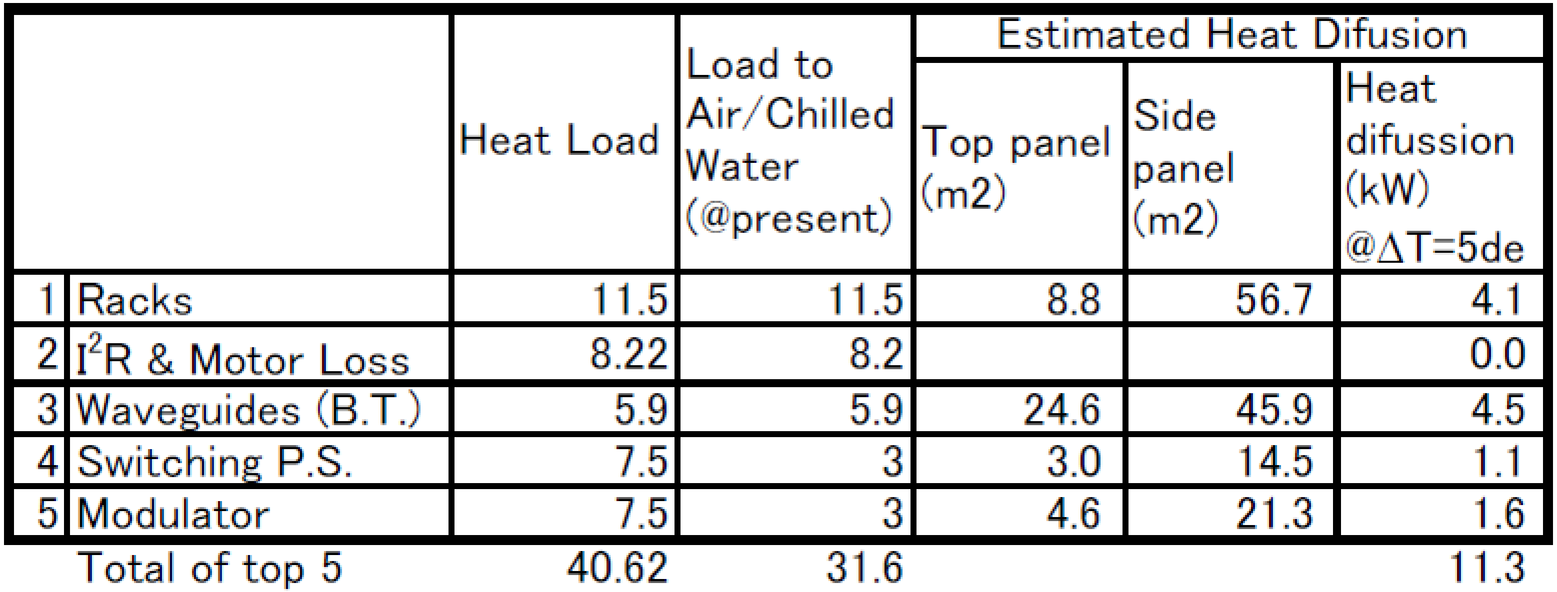
Suppress the Heat load to Air!

Heat load to air by RF equipment when LCW used

Estimated diffusion when ΔT = 5 deg, ε = 1, w = 0.45 m/s

T: Equipment temperature (34 C)

T_a: Ambient temperature (29 C)



		Heat Load	Load to Air/Chilled Water (@present)	Estimated Heat Difusion		
				Top panel (m2)	Side panel (m2)	Heat difusion (kW) @ΔT=5de
1	Racks	11.5	11.5	8.8	56.7	4.1
2	I^2R & Motor Loss	8.22	8.2			0.0
3	Waveguides (B.T.)	5.9	5.9	24.6	45.9	4.5
4	Switching P.S.	7.5	3	3.0	14.5	1.1
5	Modulator	7.5	3	4.6	21.3	1.6
	Total of top 5	40.62	31.6			11.3

Effects of Heat Insulator

----- 釈迦に説法 (Preaching Budda) -----

Heat radiation and convection

assume $\varepsilon = 1.0$ and $w = 0.45$ m/s (27 m/min)

$h = 12 \sim 18\ \mathrm{W/m^2/K}$ (for $\Delta T = 5 \sim 25$ deg)

$R_{se} = 0.056 \sim 0.083\ \mathrm{W^{-1}m^2K}$

Heat resistance of insulator (1 mm)

$R_i = d/\lambda = 0.020\ \mathrm{W^{-1}m^2K}$

d: Thickness of the material (0.001 m)

λ : Thermal conductivity of insulator ($0.05\ \mathrm{Wm^{-1}K^{-1}}$)

- A few mm of heat insulator is comparable to surface resistance

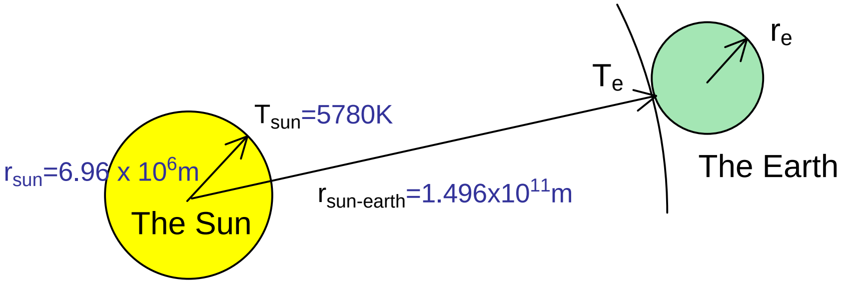
- A few cm of heat insulator is usually enough for completeness of water cooling system

Ambient Temperatures

Surface and Underground

Earth Temperature

-- as a short note --



Solar constant

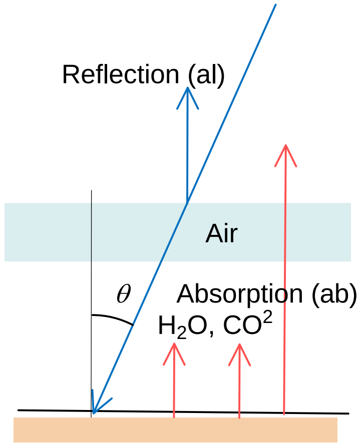
$$q_{sun} = \sigma T_{sun}^4 \times 4\pi r_{sun}^2 / 4\pi r_{sun\text{-}earth}^2 = 1370\ W/m^2$$

Temperature of the earth

$$q_{sun}\ \pi r_e^2 = \sigma T_e^4 \times 4\pi r_e^2 \quad \text{(equilibrium)}$$

$$\Rightarrow \quad T_e = 279\ K\ (6\ C)$$

Temperture on the ground depends on site



$$q_{sun} \times \cos\theta\,(1\text{-}al) = \sigma T_g^4\,(1\text{-}ab) \quad \text{(equilibrium)}$$

$\cos\theta = \sin\Theta\cos\omega_d t\cos\omega_y t + \sin\Theta\sin\omega_d\cos\mu\sin\omega_y t + \cos\Theta\sin\mu\cos\omega_y t$

Θ: latitude, μ=23.5 deg,

$\omega_d=2\pi$/day, $\omega_y=2\pi$/year

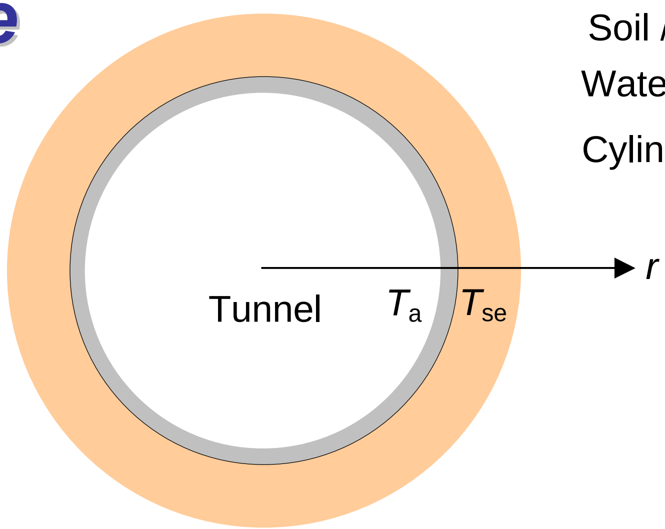
Temperature affects surface cooling towers

	d	m	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	sep	Oct	Nov	Dec		
Moscow-Dolgoprudnyj	55	50	-7.5	-6.7	-1.4	6.4	12.8	17.1	18.4	16.5	10.8	5.0	-1.6	-5.5	5.3	1971-2000
Chicago-Ohare	41	59	-5.6	-2.8	3.0	9.0	15.1	20.4	23.4	22.4	18.0	11.4	4.3	-2.2	9.7	1971-1999
Zurich-Town	47	23	0.3	1.3	5.1	8.1	12.8	15.6	18.0	17.7	14.0	9.3	4.1	1.5	9.0	1971-2000
Berlin-tempelhof	52	28	0.8	1.5	4.9	8.7	14.2	17.2	19.2	18.8	14.5	9.6	4.9	2.0	9.7	1971-2000
Tokyo	35	41	5.8	6.1	8.9	14.4	18.7	21.8	25.4	27.1	23.5	18.2	13.0	8.4	15.9	1971-2000

Place	Altitude		Relative Humidity Monthly Average												Annual Average	
	d	m	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	sep	Oct	Nov	Dec		
Moscow-Dolgoprudnyj	55	50	80	76	73	67	64	63	69	74	78	79	82	82	74	1961-1967
Chicago-Ohare	41	59	72	72	70	65	64	66	69	71	71	69	73	76	70	1961-1990
Zurich-Town	47	23	85	80	75	72	73	74	73	77	81	84	84	85	79	1961-1990
Berlin-tempelhof	52	28	89	83	76	68	64	61	65	69	73	79	87	89	75	1961-1967
Tokyo	35	41	50	51	57	62	66	73	75	72	72	66	60	53	63	1971-2000

Detail design and comparison of site difference are the next step after the system optimizaton.

Beam Tunnel Temperature



Soil / Rock

Water Table

Cylinder Model

Tunnel Air temperature without wall loss

$\Delta T = P/(Fc)$

P:heat load [W],
F: air flow [g/s],
c: specific heat capacity [J/(gK)]

When,
$P = 5.9$ kW x 104 = 0.61 MW,
$F = 7.16\ m^3/s$ (=π x $2.25^2\ m^2$ x 0.45 m/s)
$\rho = 1184\ g/m^3$
c = 1.020 J/(gK) (hum~50%)
$\Delta T \sim 70$ deg!

Heat Diffusion into tunnel wall
$q = h\,\Delta T$

Assuming the tunnel surface heat resistance (1/h)
$h = 12 \sim 18\ W/m^2/K$ (for $\Delta T = 5 \sim 25$ deg)

$S = \pi$ x 4.5 m x 36 m ~ 500 m^2 (Tunnel wall / RF init)
$Sh = 6 \sim 9$ kW /K

How is Underground Temperature ?

Depend on the geology

Deeper than 10 m, the temperature is constant

Geothermal heat flow forward the surface ground

$\sim 40 \times 10^{12} / 4\pi(6.4 \times 10^{6})^{2} = \sim 0.08\ \mathrm{W/m^{2}}$

the total geothermal heat of the earth (W) / the surface area of the Earth (m^2)

Temperature rise in deep underground

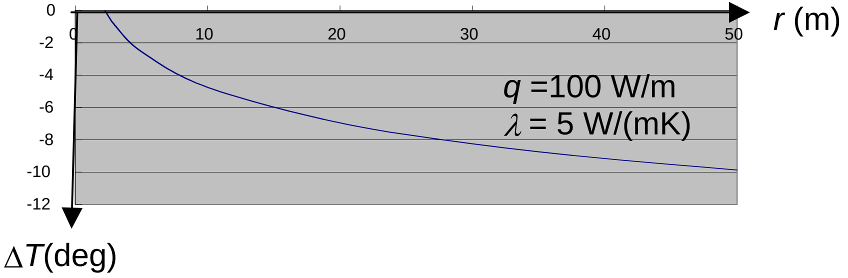
$\sim 0.08 / (2\sim 8) = 0.01\sim 0.04\ \mathrm{K/m}$

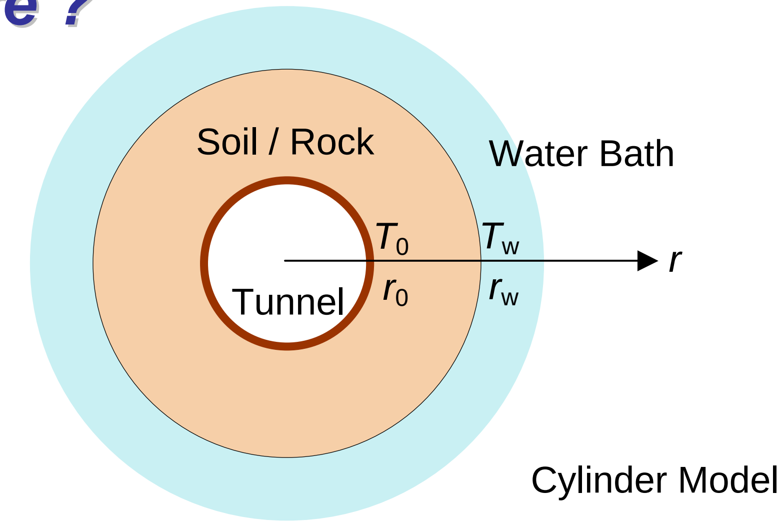
Heat flow (W/m^2) / the thermal conductivity (W/mK)

How is tunnel wall Temperature ?

Cylinder Model

$$\Delta T = -q \ln (r_w/r_0) / 2\pi\lambda$$

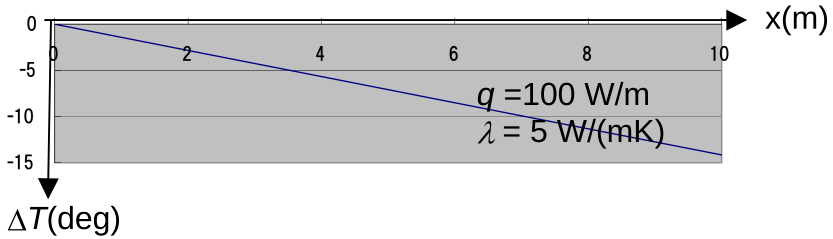


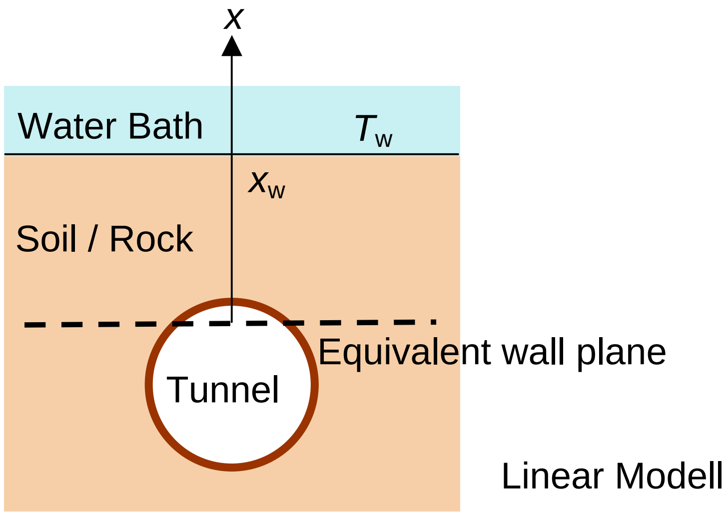


Assuming a bath, r_w-r_0 = 50 m, ΔT = 10 deg, 100 W/m could be removed from the tunnel

Linear Model

$$\Delta T = -Q x/\lambda, \quad Q = q \times 2\pi r \text{ (guess)}$$





Assuming a bath, r_w-r_0 = 7 m, ΔT = 10 deg, 100 W/m could be removable

Summary

(1) Delta T increase and Chilled Water Decrease are potential measures to reduce cooling costs.

(2) Effect of high ΔT to room T may be suppressed by insulator with relative low cost.

(3) Effect of high ΔT to equipment and beam instability should be studied separately.

(4) Alternative air cooling system using package air conditioner is under consideration.

(5) More investigation and effort to decrease heat load to air are necessary.

(6) Cooling effect by tunnel wall depends on geology of the site, though an order of ~100 W/m may be cooled under some conditions.

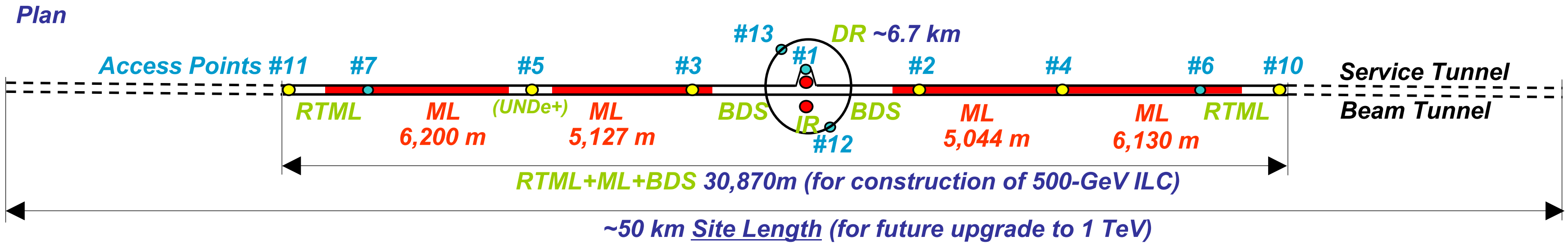
(7) LCW skid loop with complicated piping is another impact to raise cooling cost but the study is a subject to be solved hereafter.

Appendix

RF unit configuration

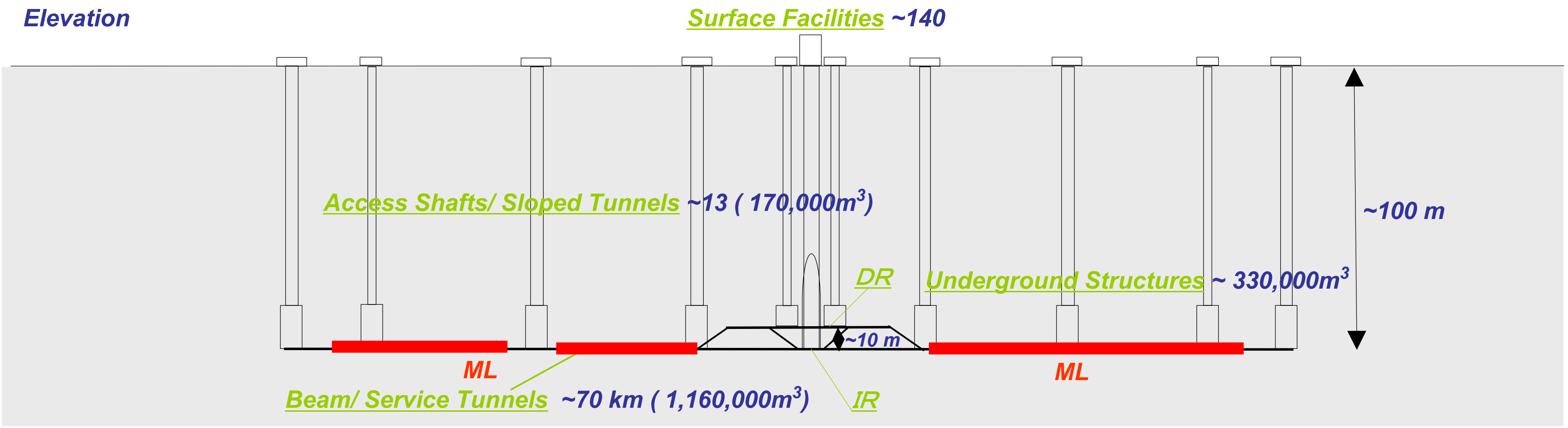
ILC Tunnel Complex and Access Points

- 31 km long Site Length with 11 access points for 500-GeV machine

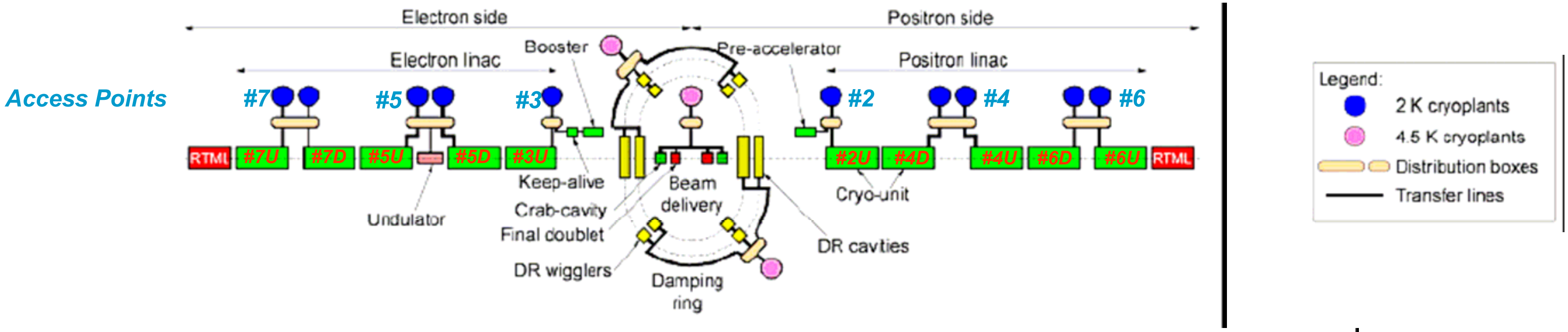


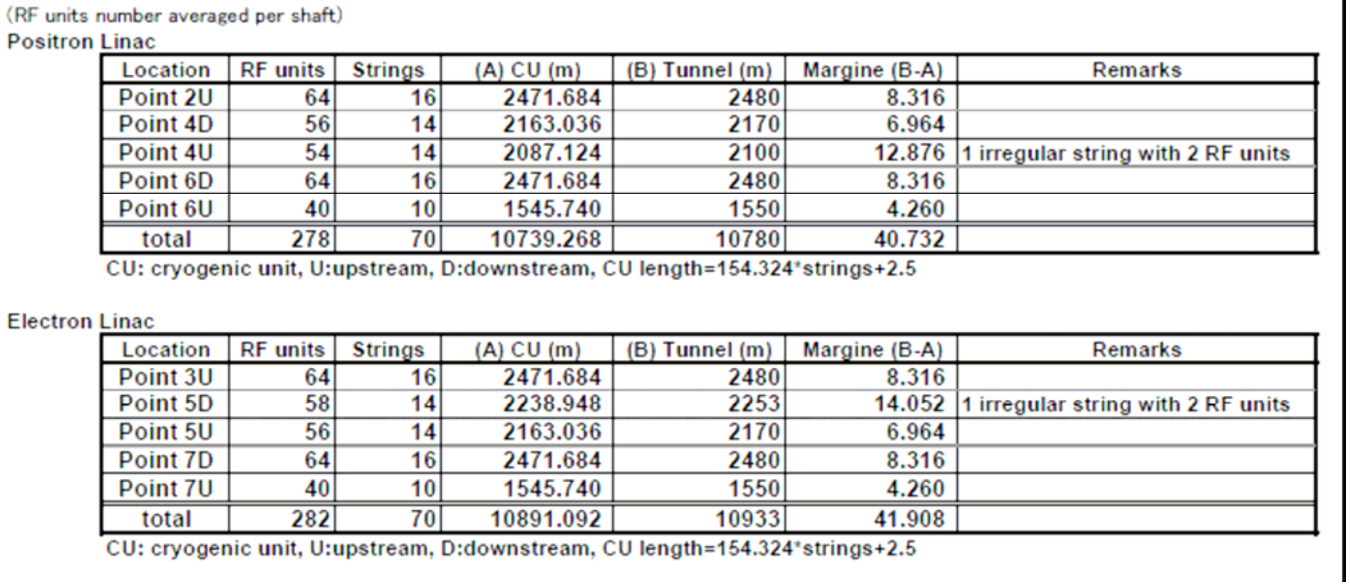
Main Linac Site Length = 22,501 km (72.9% of 30,870m)

Main Linac Tunnel Length = 44,214 km (61.4% of 72,016m)



Main Linac Configuration





(RF units number averaged per shaft)

Positron Linac

Location	RF units	Strings	(A) CU (m)	(B) Tunnel (m)	Margine (B-A)	Remarks
Point 2U	64	16	2471.684	2480	8.316	
Point 4D	56	14	2163.036	2170	6.964	
Point 4U	54	14	2087.124	2100	12.876	1 irregular string with 2 RF units
Point 6D	64	16	2471.684	2480	8.316	
Point 6U	40	10	1545.740	1550	4.260	
total	278	70	10739.268	10780	40.732	

CU: cryogenic unit, U:upstream, D:downstream, CU length=154.324*strings+2.5

Electron Linac

Location	RF units	Strings	(A) CU (m)	(B) Tunnel (m)	Margine (B-A)	Remarks
Point 3U	64	16	2471.684	2480	8.316	
Point 5D	58	14	2238.948	2253	14.052	1 irregular string with 2 RF units
Point 5U	56	14	2163.036	2170	6.964	
Point 7D	64	16	2471.684	2480	8.316	
Point 7U	40	10	1545.740	1550	4.260	
total	282	70	10891.092	10933	41.908	

CU: cryogenic unit, U:upstream, D:downstream, CU length=154.324*strings+2.5

Main Linac RF units

Plan

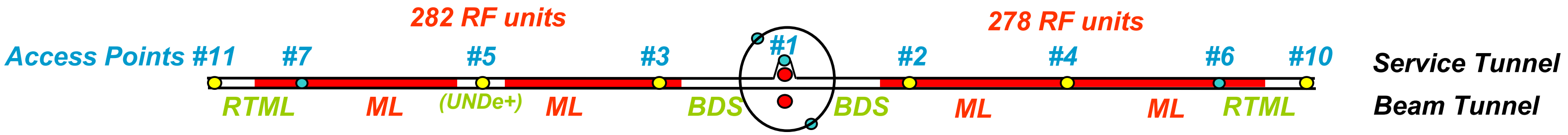
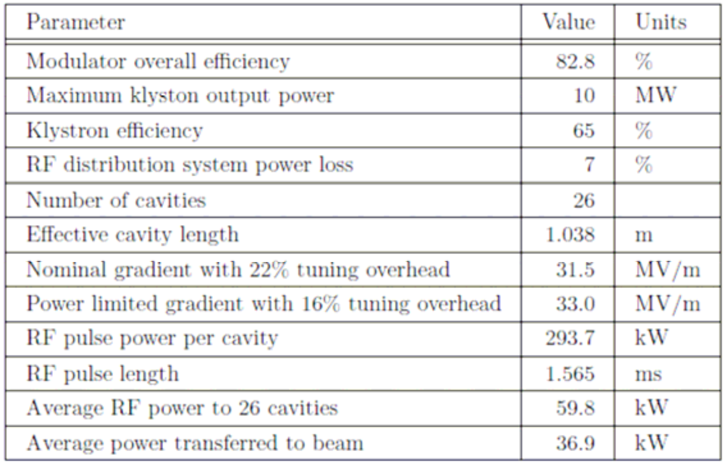
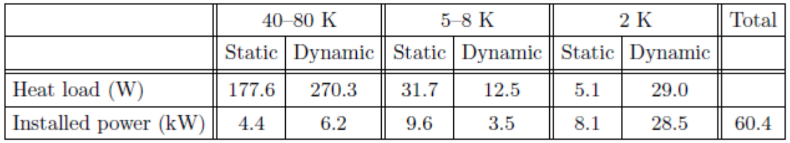


TABLE 2.6-2
RF unit parameters.



Parameter	Value	Units
Modulator overall efficiency	82.8	%
Maximum klyston output power	10	MW
Klystron efficiency	65	%
RF distribution system power loss	7	%
Number of cavities	26	
Effective cavity length	1.038	m
Nominal gradient with 22% tuning overhead	31.5	MV/m
Power limited gradient with 16% tuning overhead	33.0	MV/m
RF pulse power per cavity	293.7	kW
RF pulse length	1.565	ms
Average RF power to 26 cavities	59.8	kW
Average power transferred to beam	36.9	kW

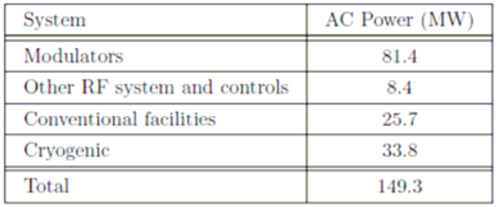
TABLE 2.6-3
RF unit cryogenic heat loads and installed AC cryogenic plant power to remove the heat.



	40–80 K		5–8 K		2 K		Total
	Static	Dynamic	Static	Dynamic	Static	Dynamic	
Heat load (W)	177.6	270.3	31.7	12.5	5.1	29.0	
Installed power (kW)	4.4	6.2	9.6	3.5	8.1	28.5	60.4

- ***Main Linac uses 560 RF units.***
- ***4 more units are used in electron linac side to compensate energy loss by undulator for positron production.***

TABLE 2.6-5
AC power consumption of the two main linacs.



System	AC Power (MW)
Modulators	81.4
Other RF system and controls	8.4
Conventional facilities	25.7
Cryogenic	33.8
Total	149.3