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Comparisons of ERLC and ILC
focusing on AC Power and Costs

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In cooperation with

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Acknowledgements to:

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Outline

- Overview
- General Comparisons

- How to compare Thermal Loads?
  - RF dynamic thermal load to Cryogenics
  - HOM absorption, thermal load to Cryogenics
- AC (wall-plug) Power Comparison of ERLC with ILC
  - Some examines to seek for minimizing AC (wall-plug) power
- Cost comparison of ERLC with ILC

- Further questions and issues to be settled

Overview

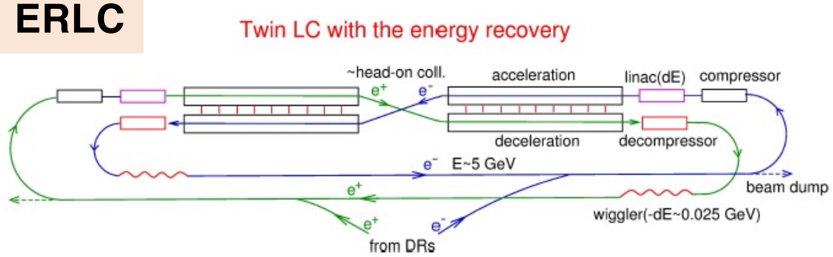
- ERLC requires **significant AC (wall-plug) power** consumption mainly for cryogenics loaded by RF dynamic loss because of RF voltage and HOM load because of beam current, under CW mode, even though the duty factor limited to 1/3. It is un-acceptably high, if the CM and HOM absorption design as similar as that of ILC.
- To significantly reduce the AC power, ERLC-CM designs needs to be based on:
  - Efficient CM design with **twin aperture SRF cavities** in common Cryomodules,
  - **HOM loads extracted** directly to much higher temperature (~50 ~ 100K)
    - HOM absorber/dumper at **each cavity end** (instead of each CM end)
  - It results **in longer CM** and and ML lengths, and additional cost.
- The design with reduced N per bunch (and/or increased bunch distance) and a full CW mode (DF=1) remains as a possibility for the proposal to be more practical, with the luminosity to be reasonably compromised.
- The construction cost would be relatively much higher than that estimated to ILC.
- Long term development will be necessary to demonstrate and establish the technology for the project realization: twin aperture cavity, frequent HOM load extraction, thermal & cryogenics design optimization, and others.

ERLC and ILC

Table 2. Parameters of e^+e^- linear colliders ERLC and ILC.

	unit	ERLC	ILC
Energy $2E_0$	GeV	250	250
Luminosity $\mathcal{L}_{\rm tot}$	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	48	~~0.75~~ → 1.35
Duty cycle		1/3	
Accel. gradient, G	MV/m	20	31.5
Cavity quality, Q	10^{10}	3	1
Length $L_{\rm act}/L_{\rm tot}$	km	12.5/22	8/20
P (wall)	MW	~130	~~128~~ → 110
N per bunch	10^{10}	0.5	2
Bunch distance	m	1.5	166
Rep. rate, f	Hz	2×10^8	6560
Norm. emit., $\epsilon_{x,n}$	10^{-6} m	20	10
Norm. emit., $\epsilon_{y,n}$	10^{-6} m	0.035	0.035
β_x^* at IP	cm	25	1.3
β_y at IP	cm	0.03	0.04
σ_x at IP	μm	4.5	0.73
σ_y at IP	nm	6.1	7.7
σ_z at IP	cm	0.03	0.03
σ_E/E_0 at IP	%	0.2	~ 1

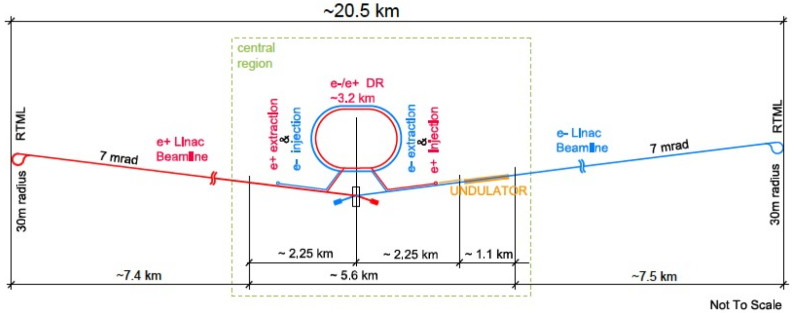
ERLC



A high luminosity superconducting twin e^+e^- linear collider with energy recovery

ILC

DESY 19-037, FERMILAB-FN-1067-PPD, IFIC/19-10
IRFU-19-10, JLAB-PHY-19-2854, KEK Preprint 2018-92
LAL/RT 19-001, PNNL-SA-142168, SLAC-PUB-17412
March 2019



The International Linear Collider
A Global Project

ILC parameters most updated

https://arxiv.org/abs/1711.00568

reference			Z-Pole (a)	Z-Pole Lum Up (a)	Higgs (b)	Higgs Lum Up (b)	Higgs L Up,10Hz (b)(d)	500GeV Baseline (c)	500GeV Lum Up (c)	TeV case B (c)
Center-of-Mass Energy	E_{CM}	GeV	91.2	91.2	250	250	250	500	500	1000
Beam Energy	E_{beam}	GeV	45.6	45.6	125	125	125	250	250	500
Collision rate	f_{col}	Hz	3.7	3.7	5	5	10	5	5	4
Electron linac rep.rate		Hz	3.7+3.7	3.7+3.7	5	5	10	5	5	4
Pluse interval in electron main linac		ms	135	135	200	200	100	200	200	200
Electron energy for e+ production		GeV	125	125	125	125	125	250	250	500
Number of bunches	n_b		1312	2625	1312	2625	2625	1312	2625	2450
Bunch population	N	10^{10}	2	2	2	2	2	2	2	1.737
Bunch separation	Δt_b	ns	554	554	554	366	366	554	366	366
Beam current		mA	5.79	5.79	5.79	8.75	8.75	5.79	8.75	7.60
Average beam power at IP (2 beams)	P_B	MW	1.42	2.84	5.26	10.5	21.0	10.5	21.0	27.3
RMS bunch length at ML & IP	σ_z	mm	0.41	0.41	0.30	0.30	0.30	0.30	0.30	0.225
RMS electron energy spread at IP	σ_p/p	%	0.30	0.30	0.188	0.188	0.188	0.124	0.124	0.085
RMS positron energy spread at IP	σ_p/p	%	0.30	0.30	0.150	0.150	0.150	0.070	0.070	0.043
Electron polarization	P_-	%	80	80	80	80	80	80	80	80,000
Positron polarization	P_+	%	30	30	30	30	30	30	30	30,000
Emittance from DR (x)	$\gamma\varepsilon^{DR}_x$	μm	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Emittance from DR (y)	$\gamma\varepsilon^{DR}_y$	nm	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Emittance at main linac end (x)	$\gamma\varepsilon^*_x$	μm	5.0	5.0	5.0	5.0	5.0			
Emittance at main linac end (y)	$\gamma\varepsilon^*_y$	nm	35.0	35.0	30.0	30.0	30.0			
Emittance at IP (x)	$\gamma\varepsilon^*_x$	μm	6.2	6.2	5.0	5.0	5.0	10.0	10.0	10.0
Emittance at IP (y)	$\gamma\varepsilon^*_y$	nm	48.5	48.5	35.0	35.0	35.0	35.0	35.0	30.0
Beta_x at IP	β^*_x	mm	18	18	13	13	13	11	11	11
Beta_y at IP	β^*_y	mm	0.39	0.39	0.41	0.41	0.41	0.48	0.48	0.23
Beam size at IP (x)	σ^*_x	μm	1.118	1.118	0.515	0.515	0.515	0.474	0.474	0.335
Beam size at IP (y)	σ^*_y	nm	14.56	14.56	7.66	7.66	7.66	5.86	5.86	2.66
Disruption Param (x)	Dx		0.41	0.41	0.52	0.52	0.52	0.31	0.31	0.20
Disruption Param (y)	Dy		31.8	31.8	35.0	35.0	35.0	24.9	24.9	25.3
Average Upsilon parameter	Yav		0.003	0.003	0.028	0.028	0.028	0.062	0.062	0.203
Geometric luminosity	Lgeo	$10^{34}/cm^2/s$	0.095	0.190	0.529	1.058	2.116	0.751	1.504	2.64
Luminosity	L	$10^{34}/cm^2/s$	0.205	0.410	1.35	2.70	5.40	1.79	3.60	4.66
Luminosity enhancement factor	H_D		2.16	2.16	2.55	2.55	2.55	2.38	2.39	1.76
Luminosity at top 1%		%	99.0	99.0	74	74	74	58	58	45
Number of beamstrahlung photons	n_γ		0.841	0.841	1.91	1.91	1.91	1.82	1.82	2.05
Beamstrahlung energy loss	δ_{BS}	%	0.157	0.157	2.62	2.62	2.62	4.5	4.5	10.5
AC power		MW	???		111	138	198	173	215	300

AC Wall-Plug Power of ERLC and ILC

AC Power Summary:		ERLC as proposed by V.T.	ERLC w/ missing AC added		ILC
SRF frequency	GHz	1.3	1.3		
e- Source total	MW	2.5	2.5		4.9
e+ Source total	MW				9.3
DR / Radiation in Wiggler	MW	5.3	5.3		14.2
RTML	MW				10.4
ML total	MW	122	139		49
RF for Beam Acc.		30	30.0		24.4
Cryog (RF, other load)		92.0	92.0		14.1
(Cryog (HOM)		0.0	0.0		1.3
CF-Utilities			16.5		10.5
BDS	MW		9.3		9.3
Dumps	MW		0.0		1.2
AC Power Accelerator	MW	130	156		98
IR/MDI	MW		5.8		5.8
Main Campus	MW		2.7		2.7
General Margin	MW		3.3		3.3
Total AC Power	MW		167		110

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- Further questions and issues to be studied

How to compare the ERLC and ILC ?

Convenient Relations:

Luminosity: $\propto N \times DF$ *(if N/sig-x = const)*

HOM: $\propto N^2/d \times L_{act}$ *or* $N \times \langle I_{av} \rangle \times L_{act}$

$\propto 1/a^2$

$P_{\text{-RF-LOSS}} = V^2/\{(R/Q)\, Q_o\}$

$$P_{diss} = \frac{V_{acc}^2}{(R/Q)/Q_0},$$

Eq. 6.1 in Telnov's report:

$P_{\text{-HOM}} = \{265/d\ [m]\} \times (N/10^{10})^2 \times (L\text{-act}/25\ (km/km))$ *[MW]*

$$P_{HOM} = \frac{265}{d[m]}\left(\frac{N}{10^{10}}\right)^2 \text{MW}.$$

Eq. 5.3 in Telnov's report

DF: Duty factor

N: # particle / bunch

d: bunch separation distance [m]

L-act: Active Accelerator Length [m]

a: Cavity Aperture Radius [mm]

G: Acc. Gradient [MV/m]

R/Q: Shunt impedance

(1035 Ω at 1.3 GHz elliptical)

E: Voltage [MV]

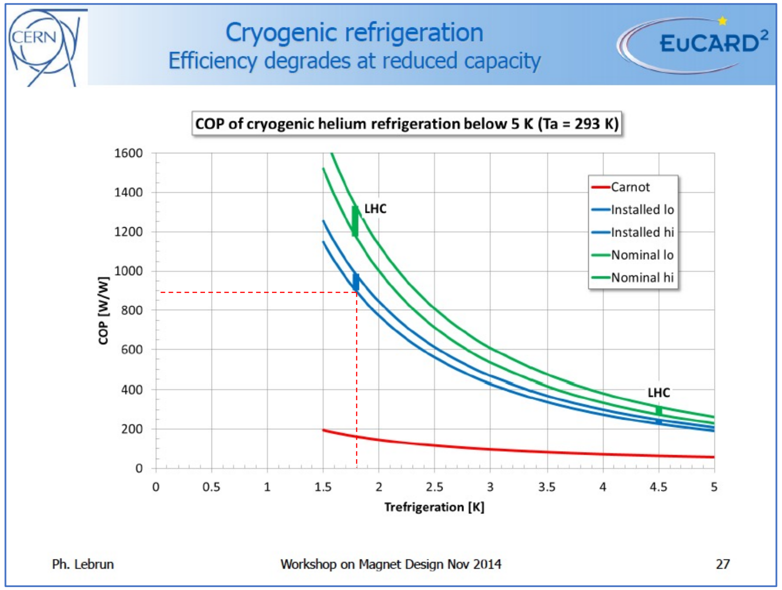
Q_0: Quality Factor

Comparisons of ERLC and ILC

RF Dynamic Loss for Cryogenics:

$P_{RF\text{-}loss} = V^2 / \{(R/Q)\ Q_o\} \times L$

- $P_{\text{-RF-ERLC}} = \{(20e6\ [V/m]\}^2 / \{1.036e3\ [\Omega] \times 3e10\} \times (2\times12.5)e3\ [m]$
  = 3.22 e5 = 322 kW at DF = 1
  → 322 KW x 1/3 = 107 kW at DF = 1/3
  → 107 x 900 = **~ 100 MW** at TE^{-1} = 901 (at 1.8K)
- $P_{\text{-RF-ILC}} = \{31.5e6\ V/m \times 1.04\ m\}^2 / \{1.036e3\ \Omega \times 1e10\} \times 7.94e3\ m$
  = 8.22 e5 = 822 KW at DF =1
  → 822 KW x 0.00825 = 6.78 kW at PD: 1.65 ms x 5 Hz
  → 6.78 x 790 = **5.4 MW** at TE^{-1} =790 (at 2 K)
- $\{P_{RF\text{-}ERLC} / P_{RF\text{-}ILC}\}$ = ~18.5



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Comparisons of ERLC and ILC

HOM Loss Thermal Load for Cryogenics :

$P_{\text{-HOM-loss}}$ = {265/d} x {N/10^{10}}^{2} x {L-act/25} (km/km)} [MW]

- $P_{\text{-HOM-ERLC}}$ = {265/1.5 } x {0.5e10/1e10}^{2} (25/25) = 44.2 MW
  - → 44.2 MW x 1/3 = 14.7 MW at DF = 1/3
  - → 14.7 x <TE^{-1}> = 1,235 MW at <TE^{-1}> = ~84 (1.8, 6, 50, (RT), distributed, as same as ILC (CM)
  - = 191 MW at < TE^{-1}> = ~ 13, if HOM load extracted to 80 K, (RT) as similar as CBETA (MLC)

- $P_{\text{-HOM-ILC}}$ = {265/166} x {2e10/1e10}^{2} x (7.94/25) = 2.03 MW
  - → 2.03 x 0.00364 = 7.4 kW at DF = 0.000726 ms x 5Hz
  - → 7.4 x <TE^{-1}>* = 620 kW at <TE^{-1}> = ~84 , if HOM load extracted to 1.8, 6, 50, (RT), distributed as same as ILC (CM)
  - = 96 kW at < TE^{-1}> = ~ 13, if HOM load extracted to 80 K , (RT) as similar as CBETA (MLC)

*note: <TE^{-1}> : Averaged Thermal Efficiency (Carnot x mechanical eff.) :

- **{$P_{\text{-HOM-ERLC}}$ / $P_{\text{-HOM-ILC}}$} = ~2,000**

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Table 3.1
Summary of key numbers for the SCRF Main Linacs for 500 GeV centre-of-mass-energy operation. Where parameters for positron and electron linacs differ, the electron parameters are given in parenthesis.

Cavity (nine-cell TESLA elliptical shape)		
Average accelerating gradient	31.5	MV/m
Quality factor Q_0	10^{10}	
Effective length	1.038	m
R/Q	1036	Ω
Accepted operational gradient spread	±20%	
Cryomodule		
Total slot length	12.652	m
Type A	9 cavities	
Type B	8 cavities	1 SC quad package
ML unit (half FODO cell)	282 (285)	units
(Type A - Type B - Type A)		
Total component counts		
Cryomodule Type A	564 (570)	
Cryomodule Type B	282 (285)	
Nine-cell cavities	7332 (7410)	
SC quadrupole package	282 (285)	
Total linac length – flat top.	11027 (11141)	m
Total linac length – mountain top.	11072 (11188)	m
Effective average accelerating gradient	21.3	MV/m
RF requirements (for average gradient)		
Beam current	5.8	mA
beam (peak) power per cavity	190	kW
Matched loaded Q (Q_L)	5.4×10^6	
Cavity fill time	924	μs
Beam pulse length	727	μs
Total RF pulse length	1650	μs
RF–beam power efficiency	44%	

Heat loads of ILC CM from TDR

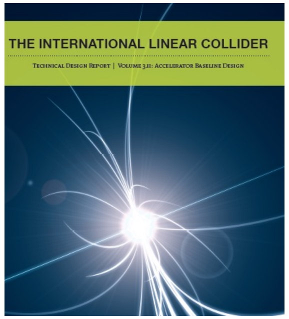


Table 3.9 Average heat loads per module in a ML unit, for the baseline parameter in Table 3.1. All values are in watts [27].

	2 K		5–8 K		40–80 K	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
RF Load		8.02				
Radiation Load			1.41		32.49	
Supports	0.60		2.40		18.0	
Input coupler	0.17	0.41	1.73	3.06	16.47	41.78
HOM coupler (cables)	0.01	0.12	0.29	1.17	1.84	5.8
HOM absorber	0.14	0.01	3.13	0.36	-3.27	7.09
Beam tube bellows		0.39				
Current leads	0.28	0.28	0.47	0.47	4.13	4.13
HOM to structure		0.56				
Coax cable (4)	0.05					
Instrumentation taps	0.07					
Diagnostic cable			1.39		5.38	
Sum	1.32	9.79	10.82	5.05	75.04	58.80
Total	11.11		15.87		133.84	

Note:
To be checked, if HOM loads for 1,312 bunches or 2,065 ?? in an old baseline design

RF load (2K): 8.02 W
HOM load (2K): 0.12+0.01+0.39+0.56 = 1.08 W

ILC CM Thermal Load: Overall and HOM

Overall /CM	Unit	Heat Load				SUM
Parameter		at 2K, [W]	at 5-8 K[W]	at 40 - 80 K [W}	(RT)	
Overall	W /module	11.11	15.87	133.84		161
Thermal eff. Invserse		(790)	(208)	(21)		
(conversion)		(300/2/0.19)	(300/6/0.24)	(300/50/0.28)		
Corresp, AC Power (@RT)/CM	W / mocule	8777	3301	2811		14,889 (- ~5%)
Total, AC Power for 886 CM	MW/900 CM					**13.2**
						15.3 include. margin
						Correction { -5%}:
HOM / CM	**Unit**	**Heat Load**				**SUM**
Parameter		at 2K, [W]	at 5-8 K[W]	at 40 - 80 K [W}	(RT)	
HOM related	W /module	1.08 / 2	1.53 / 2	12.89 / 2	(1,83 / 2)	15.5 / 2
Thermal eff. Invserse		(790)	(210)	(21)	(1)	
(conversion)		(300/2/0.19)	(300/6/0.24)	(300/50/0.28)	(300/300)	
Corresp, AC Power (@RT) /CM	W / module	853 / 2	318 / 2	271 / 2	1.83 / 2	1,444 / 2
Total, AC Power for 886 CM	MW/886 CM					**1.28 / 2**
						4~5 % to overall.

Assumptions: Each HOM loads to be divided by 2, because of a historical reason in the ILC-TDR process (Ref., KY).

HOM Cryogenic and AC-Power Load /CM for ERLC and ILC:
with same CM string design applied for HOM load extraction

ERLC	Unit	Heat Load				SUM
Parameter		at 2K, [W]	at 5-8 K[W]	at 40 - 80 K [W}	(RT)	
Overall	W /module (Twin)	685	970	8,180	1,100	10,935
Thermal eff. Invserse		(901)	(208)	(21)		
(conversion)		(300/2/0.185)	(300/6/0.24)	(300/50/0.28)		
Corresp, AC Power (@RT)/CM	W / mocule (Twin)	617,185	201,760	171,780	1,100	991,825
Total, AC Power for 1390 CM	MW/1390 CM					1,380

ERLC / ILC = 2,000

ILC	Unit	Heat Load				SUM
Parameter		at 2K, [W]	at 5-8 K[W]	at 40 - 80 K [W}	(RT)	
HOM related	W /module	1.08 / 2	1.53 / 2	12.89 / 2	(1,83) / 2	15.5 / 2
Thermal eff. Invserse		(790)	(210)	(21)	(1)	
(conversion)		(300/2/0.19)	(300/6/0.24)	(300/50/0.28)	(300/300)	
Corresp, AC Power (@RT) /CM	W / module	853 / 2	318 / 2	271 / 2	1.83 / 2	1,444 / 2
Total, AC Power for 886 CM	MW/886 CM					1.28 / 2

HOM Load Comparison between ERLC and ILC

		ERLC (1.3 GHz)	ILC	ERLC / ILC
f	GHz	1.3	1.3	
N: (e-_e+) / bunch	10^10	0.5	2	0.25
Dt (bunch distance)	ns	5	554	1/111
I (pulse)	mA	160	5.78	27.7
Duty cycle		1/3	554ns*1312/200ms 0.00363	91.7
I (average)	mA	53.3	0.021	2540
Accelerating gradient	MV/m	20	31.5	0.635
L (including deceleration, both e+ and e-)	km	125GV/(20MV/m) *2 *2=25 km	125GV/(31.5/MV/m) *2=7.937 km	3.15
N * I-av * L		666	0.333	**2000**
HOM Load:	MW	1260 *(To be confirmed !)*	1.26* (1/2)	

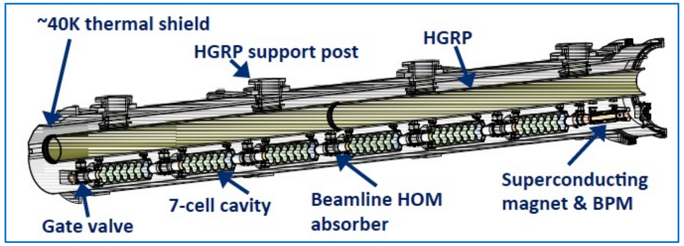
AC Wall-Plug Power of ERLC and ILC

AC Power Summary:		ERLC as proposed by V.T.	ERLC w/ missing AC added	ILC
SRF frequency	GHz	1.3	1.3	
e- Source total	MW	2.5	**2.5**	**4.9**
e+ Source total	MW			**9.3**
DR / Radiation in Wiggler	MW	**5.3**	**5.3**	**14.2**
RTML	MW			**10.4**
ML total	MW	**122**	**139**	**49**
RF for Beam Acc.		30	30.0	24.4
Cryog (RF, other load)		92.0	92.0	14.1
(Cryog (HOM)		0.0	0.0	1.3
CF-Utilities			16.5	10.5
BDS	MW		**9.3**	**9.3**
Dumps	MW		**0.0**	**1.2**
AC Power Accelerator	MW	**130**	**156**	**98**
IR/MDI	MW		5.8	**5.8**
Main Campus	MW		2.7	**2.7**
General Margin	MW		3.3	**3.3**
Total AC Power	MW		**167**	**110**

Our Estimate for ERLC thermal loads, and Various Examines to reduce AC (wall-pug) Power

- An Issue
- ERLC HOM load **becomes x 2000 times** that of ILC,
  - Resulting in **>1.2 GW AC** (wall-plug) power for HOM
    - **if** the same ML CM design at HOM absorber at CM end, with HOM distributed **absorption at 1.8, 5–8, 40 – 80K,**

- Various examines to find solution to reduce AC (wall-plug) power:
  - **HOM load extraction to higher temperature** (80 K or higher)
    - It requires HOM absorber at each cavity end, referring CBETA-MLC
      - *→ Thanks for Chris' advice and references.*
  - **Increasing Iris radius** → Lower SRF frequency



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Convenient Relations:

Luminosity: $\propto N \times DF$ *(if N/sig-x = const)*

HOM: $\propto N^2/d \times L_{act}$ or $N \times \langle I_{av} \rangle \times L_{act}$

$\propto 1/a^2$

$$P_{diss} = \frac{V_{acc}^2}{(R/Q)/Q_0},$$

Eq. 6.1 in Telnov's report:

$$P_{\text{-RF-LOSS}} = V^2/\{(R/Q)\ Q_o\}$$

$$P_{\text{-HOM}} = \{265/d\ [m]\} \times (N/10^{10})^2 \times (\text{L-act}/25\ (km/km))\quad [MW]$$

$$P_{\text{HOM}} = \frac{265}{d[\text{m}]}\left(\frac{N}{10^{10}}\right)^2 \text{MW}.$$

Eq. 5.3 in Telnov's report

DF: Duty factor

N: # particle / bunch

d: bunch separation distance [m]

L-act: Active Accelerator Length [m]

a: Cavity Aperture Radius [mm]

G: Acc. Gradient [MV/m]

R/Q: Shunt impedance
(1035 Ω at 1.3 GHz elliptical)

E: Voltage [MV]

Q_0: Quality Factor

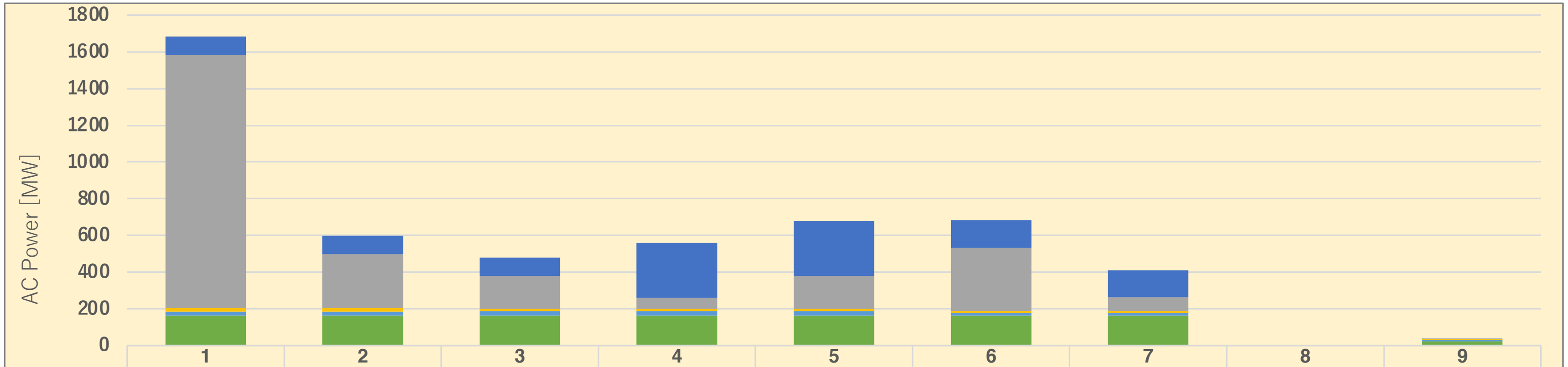
Optional Comparisons of ML AC Wall-Plug Power for ERLC and ILC

	unit	ERLC-1 HOM to 1.8K ~	ERLC-2 HOM to 50K ~	ERLC-3 HOM to 80K ~	ERLC-4 HOM to 80K ~ N/3, DF=1	ERLC-5 HOM to 80K ~d*3, DF=1	ERLC-6 HOM to 1.8K ~	ERLC-7 HOM to 50K ~	ILC HON to 2K ~
Luminosity	10E35	**4.8**	**4.8**	**4.8**	**1.6**	**4.8**	**4.8**	**4.8**	**0.135**
Frequency	GHz	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**0.65**	**0.65**	**1.3**
HOM absorber temp.	K	**1.8, 6, 50, RT**	**50, RT**	**80K, RT**	**80K, RT**	**80K, RT**	**1.8, 6, 50, RT**	**50, RT**	**2, 6, 50, (RT)**
Iris Radius	mm	35	35	35	35	35	**70**	**70**	35
Gradient	MV/m	20	20	20	20	20	20	20	31.5
L-active for SRF field	km	2x12.5	2x12.5	2x12.5 (x1.2)	2x12.5 (x1.2)	2x12.5 (x1.2)	2x12.5/22	2/12.5/22	7.94/20.5
L-tunnel (physical L.)	km	22	22	22 (x1.2)	22 (x1.2)	22 (x1.2)			
# CM (twin cavity)		1390	1390	1390	1390	1390	695	695	886
AC Wall-plug Power:									
Cryog.: Dynamic (RF)Load	MW	100	100	100	300	300	150	150	5.1
HOM (RF) Load	MW	1380	294	178	59	178	346	74	0.65
Input Coupler Load	MW	18	18	15	15	15	9	9	1.6
Static Load	MW	21	21	23	23	23	14	14	8.3
RF Power for Beam Acc.	MW	165	164	164	164	164	165	165	24
Grand total	**MW**	**1686**	**596**	**479**	**562**	**679**	**683**	**411**	**40**
Note-A:			HOM-ext T. effect, significant	~ consistent with estimate based on CBETA. design.	Same at Left, but. n/3, DF=1, L ➔ 1/3	Same at Left, but. d*3, DF=1	Iris R effect, significant	HOM-ext T. and Iris R effect	

Note-B: All cases **assuming** the Eu-XFEL like **9-cell cavity** for simplicity in comparison CBETA uses 7-cell cavity with larger beam pipe.

Optional Comparisons of ML AC Wall-Plug Power for ERLC and ILC

	unit	ERLC-1 HOM to 1.8K ~	ERLC-2 HOM to 50K ~	ERLC-3 HOM to 80K ~	ERLC-4 HOM to 80K ~ N/3, DF=1	ERLC-5 HOM to 80K ~d*3, DF=1	ERLC-6 HOM to 1.8K ~	ERLC-7 HOM to 50K ~		ILC HON to 2K ~
Luminosity	1.00E+36	4.8	4.8	4.8	1.6	4.8	4.8	4.8		0.135
Cryog, Dynamic Load	MW	100	100	100	300	300	150	150		5.1
Cryog. HOM (RF) Load	MW	1380	294	178	59	178	346	74		0.65
Cryog. Input Coupler Load	MW	18	18	15	15	15	9	9		1.6
Cryog. Static Load	MW	21	21	23	23	23	14	14		8.3
RF Power for Beam Acc.	MW	165	164	164	164	164	165	165		24
Grand total	**MW**	**1686**	**596**	**479**	**562**	**679**	**683**	**411**		**40**



	1	2	3	4	5	6	7	8	9
Dynamic Loss	100	100	100	300	300	150	150		5.1
HON Loss	1380	294	178	59	178	346	74		0.65
Input Coupler	18	18	15	15	15	9	9		1.6
Static Loss	21	21	23	23	23	14	14		8.3
RF P.(Beam Acc.)	165	164	164	164	164	165	165		24

EXEL Sheet:
Comparison-ERLC-ILC (AC-Power)--210801 (1/2)

Comparison of SRF systems for ILC-250 and ERLC

S. Belomestnykh (210716) and A. Yamamoto 's update (210801a)

2021/7/16, --> 2021/8/1

c = 3.00E+08 m/s

e = 1.60E-19 C

Parameter	Units	ERLC (1.3 GHz) HOM to 1.8, 6, 50K, RT DF=1/3	ERLC (1.3 GHz) HOM to 50K, RT DF=1/3	ERLC (1.3 GHz) HOM to 80 K, RT HOM absorber b/w cav., Resulting longer Linac. DF=1/3	ERLC (1.3 GHz) HOM to 80 K, RT HOM absorber b/w cav., Resulting longer Linac N/3, DF=1	ERLC (1.3 GHz) HOM to 80 K, RT HOM absorber b/w cav., Resulting longer Linac d*3, DF=1	ERLC (0.65 GHz) HOM to 1.8, 6, 50K, RT DF=1/3	ERLC (0.65 GHz) HOM to 50K, RT DF=1/3	ILC (1.3 GHz) HOM to 2, 6, 50K, RT
Beam energy	eV	2.50E+11	2.50E+11	2.50E+11	2.50E+11	2.50E+11	2.50E+11	2.50E+11	2.50E+11
Accel. gradient	V/m	2.00E+07	2.00E+07	2.00E+07	2.00E+07	2.00E+07	2.00E+07	2.00E+07	3.15E+07
Effective gradient	V/m	1.35E+07	1.35E+07	1.35E+07	1.35E+07	1.35E+07	1.35E+07	1.35E+07	2.13E+07
Q0		3.00E+10	3.00E+10	3.00E+10	3.00E+10	3.00E+10	4.00E+10	4.00E+10	1.00E+10
Active linac length x 2 (to evaluate AC for "twin")	m	2.50E+04	2.50E+04	2.50E+04	2.50E+04	2.50E+04	2.50E+04	2.50E+04	7.94E+03
Linac length	m	3.70E+04	3.70E+04	3.70E+04	3.70E+04	3.70E+04	3.70E+04	3.70E+04	1.17E+04
RF frequency	Hz	1.30E+09	1.30E+09	1.30E+09	1.30E+09	1.30E+09	6.50E+08	6.50E+08	1.30E+09
R/Q: Cavity shape factor	Ohm	1036	1036	1036	1036	1036	1037	1037	1036
Active cavity length	m	1.038	1.038	1.038	1.038	1.038	2.075	2.075	1.038
No. of cavities		24091	24091	24091	24091	24091	12045	12045	7648
No. of cryomodules x 2 aperture (to evaluate AC power)		2780	2780	2780	2780	2780	1390	1390	882
No. of CM for V. Vessel (to evaluate Input Coupler load)		1390	1390	1390	1390	1390	695	695	882
Cryogenics: RF-Losses:									
Cavity losses	W	13.86	13.86	13.86	13.86	13.86	41.54	41.54	103.14
Losses per meter	W/m	13.36	13.36	13.36	13.36	13.36	20.01	20.01	99.39
Total linac dynamic cavity losses at 1.8K, 2 K	W	3.34E+05	3.34E+05	3.34E+05	3.34E+05	3.34E+05	5.00E+05	5.00E+05	7.89E+05
Beam current	A	1.60E-01	1.60E-01	1.60E-01	5.34E-02	5.34E-02	1.60E-01	1.60E-01	5.80E-03
Bunch population		5.00E+09	5.00E+09	5.00E+09	1.67E+09	5.00E+09	5.00E+09	5.00E+09	2.00E+10
Bunch separation	s	5.00E-09	5.00E-09	5.00E-09	5.00E-09	1.50E-08	5.00E-09	5.00E-09	5.54E-07
Bunch separation	m	1.50	1.50	1.50	1.50	4.50	1.50	1.50	166.1
Bunches per pulse									1.31E+03
Rep rate	Hz	2.00E+08	2.00E+08	2.00E+08	2.00E+08	2.00E+08	2.00E+08	2.00E+08	5.00
Qext		1.01E+07	1.01E+07	1.01E+07	3.04E+07	3.04E+07	2.03E+07	20272672.52	5.40E+06
Cavity half-bandwidth	Hz	64	64	64	21	21	16	16	120
Cavity decay time	s	2.48E-03	2.48E-03	2.48E-03	7.45E-03	7.45E-03	9.93E-03	9.93E-03	1.32E-03
Cavity fill time	s	1.74E-03	1.74E-03	1.74E-03	5.21E-03	5.21E-03	6.94E-03	6.94E-03	9.24E-04
Beam pulse length	s								7.27E-04
RF pulse length	s	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.65E-03
RF-beam power efficiency									0.44
Duty factor (for RF-ON time)		0.333	0.333	0.333	0.999	0.999	0.333	0.333	8.26E-03
Duty factor (for Beam-ON time)									3.64E-03
Average linac dynamic cavity losses at 1.8K, 2K	W	1.11E+05	1.11E+05	1.11E+05	3.34E+05	3.34E+05	1.67E+05	1.67E+05	6.51E+03
RF: Corresponding Total AC power for Linac	W	**1.00E+08**	**1.00E+08**	**1.00E+08**	**3.01E+08**	**3.01E+08**	**1.50E+08**	**1.50E+08**	**5.14E+06**
Average RF losses at 1.8K, 2 K per (Twin, Single) CM	W	80.08	80.00	80.00	239.99	239.99	240.01	240.01	7.38
Cryogenics: HOM Losses:									
HOM power total	W	4.42E+07	4.42E+07	4.42E+07	4.91E+06	1.47E+07	1.10E+07	1.10E+07	2.03E+06
Average total HOM power	W	**1.47E+07**	1.47E+07	1.47E+07	4.90E+06	1.47E+07	3.68E+06	3.68E+06	7.37E+03
HOM power per cavity	W	1.83E+03	1.83E+03	1.83E+03	2.04E+02	6.11E+02	9.17E+02	9.17E+02	2.65E+02
Average HOM power per cavity	W	611.1	6.10E+02	6.10E+02	2.03E+02	6.10E+02	305.6	305.6	0.96
Average HOM power per CM for twin aperture	W	1.10E+04	1.10E+04	1.10E+04	3.66E+03	1.10E+04	5.50E+03	5.50E+03	8.67
Av. HOM loss at 1.8K, 2 K per CM for twin aperture	W	685.06	0.00	0.00	0.00	0.00	342.55	0.00	0.54
Av. HOM loss at 5-8 K per CM for twin aperture	W	970.50	0.00	0.00	0.00	0.00	485.27	0.00	0.77
Av. HOM loss at 40-80 K per CM for twin aperture	W	8.18E+03	9.83E+03	9.83E+03	3.28E+03	9.83E+03	4.09E+03	4.92E+03	6.45
Av. HOM to RT per CM (or to somewhere ??)	W	1.16E+03	1.16E+03	1.16E+03	3.87E+02	1.16E+03	5.81E+02	5.81E+02	0.92
Av. HOM: Correspond. AC Power/CM for twin-aperture	W	9.96E+05	2.12E+05	1.28E+05	4.28E+04	1.28E+05	4.98E+05	1.06E+05	724.82
HOM: Correspond. Total AC Power for Linac	W	**1.38E+09**	**2.94E+08**	**1.78E+08**	**5.94E+07**	**1.78E+08**	**3.46E+08**	**7.37E+07**	**639626.5**
Cryogenics: Input Couplerrs;									

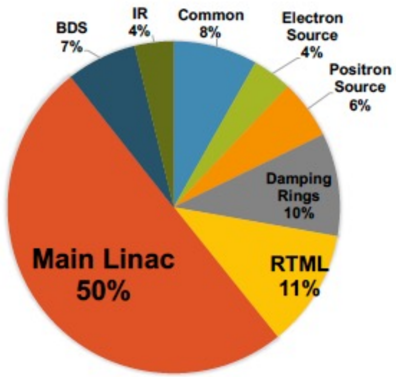
EXEL Sheet:
Comparison-ERLC-ILC (AC-Power)--210801 (1/2)

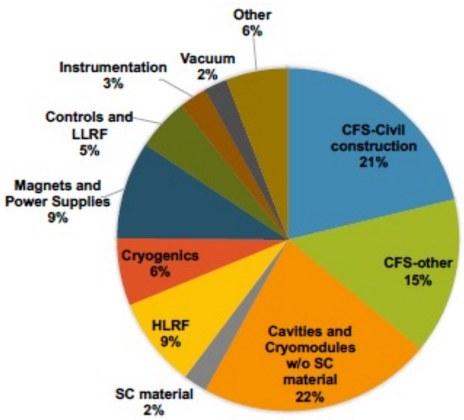
HOM: Correspond. Total AC Power for Linac	W	1.38E+09	2.94E+08	1.78E+08	5.94E+07	1.78E+08	3.46E+08	7.37E+07	639626.5
Cryogenics: Input Couplerrs;									
Input coupler loss at 1.8K, 2 K per CM	W	2.82	2.82	2.82	2.82	2.82	2.82	2.82	0.41
Input coupler loss at 5-8 K	W	21.03	21.01	21.01	21.01	21.01	21.03	21.03	3.06
Input coupler loss at 40-80 K	W	287.17	286.88	286.88	286.88	286.88	287.17	287.17	41.78
Beam tube bellows at 2 K (included in HOM)	W	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Input Coupler Correspond. AX Power / for LINAC	MW	18	18	15	15	15	9	9	1.64
Cryogenics: Statice Losses:									
Static loss at 1.8K/2 K per CM	W	9.00	9.00	10.80	10.80	10.80	12.00	12.00	6.00
Static loss at 5-8 K	W	19.48	19.48	23.37	23.37	23.37	25.97	25.97	12.98
Static loss at 40-80 K	W	135.07	135.07	162.09	162.09	162.09	180.10	180.10	90.05
Static losses, Correspond. AX Power / for LINAC	MW	20.93	20.93	23.20	23.20	23.20	13.95	13.95	8.27
Cryogenics Sum:									
Total CM heat load at 1.8K/2 K	W	776.96	91.81	93.61	253.61	253.61	597.38	254.83	14.33
Total CM heat load at 5-8 K	W	1011.01	40.49	44.38	44.38	44.38	532.27	47.00	16.81
Total CM heat load at 40-80 K	W	8.60E+03	1.03E+04	1.03E+04	3.73E+03	1.03E+04	4.56E+03	5.39E+03	138.28
Total linac heat load at 1.8K/2 K	W	1.08E+06	1.28E+05	1.30E+05	3.52E+05	3.52E+05	4.15E+05	1.77E+05	1.26E+04
Total linac heat load at 5-8 K	W	1.41E+06	5.63E+04	6.17E+04	6.17E+04	6.17E+04	3.70E+05	3.27E+04	1.48E+04
Total linac heat load at 40-80 K	W	1.20E+07	1.42E+07	1.43E+07	5.18E+06	1.43E+07	3.17E+06	3.74E+06	1.22E+05
Conversion to AC from 1.8K/2 K	*W/W*	*900.90*	*900.90*	*900.90*	*900.90*	*900.90*	*900.90*	*900.90*	*789.47*
Conversion to AC from 5-8 K	*W/W*	*208.33*	*208.33*	*208.33*	*208.33*	*208.33*	*208.33*	*208.33*	*208.33*
Conversion to AC from 40-80 K	*W/W*	*21.43*	*21.43*	*12.93*	*12.93*	*12.93*	*21.43*	*21.43*	*21.43*
Total AC power for 1.8K/2 K	W	9.73E+08	1.15E+08	1.17E+08	3.18E+08	3.18E+08	3.74E+08	1.60E+08	9.98E+06
Total AC power for 5-8 K	W	2.93E+08	1.17E+07	1.29E+07	1.29E+07	1.29E+07	7.71E+07	6.80E+06	3.09E+06
Total AC power for 40-80 K	W	2.56E+08	3.05E+08	1.85E+08	6.69E+07	1.85E+08	6.79E+07	8.02E+07	2.61E+06
Total AC power coverted to Wall Plug Power	W	1.52E+09	4.32E+08	3.15E+08	3.97E+08	5.15E+08	5.19E+08	2.47E+08	1.57E+07
Beam power per cavity	W	3.32E+06	3.32E+06	3.32E+06	1.11E+06	1.11E+06	6.65E+06	6.65E+06	1.90E+05
Total beam power	W								1.45E+09
Average total beam power	W								5.27E+06
ERLC ML fill time	s	1.23E-04	1.23E-04	1.23E-04	1.23E-04	1.23E-04	1.23E-04	1.23E-04	
ERLC beam ramp up/down time	s	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	
RF power during beam ramp up/down	W	4.10E+04	4.10E+04	4.10E+04	1.37E+04	1.37E+04	8.20E+04	8.20E+04	
RF power during energy recovery	W	1.02E+04	1.02E+04	1.02E+04	3.42E+03	3.42E+03	2.05E+04	2.05E+04	
RF Power for ML Beam Acceleration and ERL:									
Total ML RF power during pulse	W	2.47E+08	2.47E+08	2.47E+08	8.23E+07	8.23E+07	2.47E+08	2.47E+08	1.45E+09
Average ML RF power	W	8.23E+07	8.22E+07	8.22E+07	8.22E+07	8.22E+07	8.23E+07	8.23E+07	1.20E+07
AC to RF power efficiency		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Total AC power for RF	W	1.65E+08	1.64E+08	1.64E+08	1.64E+08	1.64E+08	1.65E+08	1.65E+08	**2.39E+07**
Grand total AC power	W	1.69E+09	5.96E+08	4.79E+08	5.62E+08	6.79E+08	6.83E+08	4.11E+08	3.96E+07
	MW	**1686.42**	**596.35**	**479.15**	**561.73**	**679.49**	**683.47**	**411.09**	**39.63**

Outline

- Executive Summary
- General Comparisons
- How to compare Power Consumption?
  - RF dynamic thermal load to Cryogenics
  - HOM absorption, thermal load to Cryogenics
- AC (wall-plug) Power Comparison of ERLC with ILC
  - Some examines to seek for minimizing AC (wall-plug) power
- Cost comparison of ERLC with ILC
- Further questions and issues to be studied

Thinking about Relative Costs of ERLC to ILC





	ILC [%]	Relative Ratio of ERLC to ILC	ERLC [%]	Not¥le
e- source	4	x 0.8	**3.2**	Slightly lower because of Less duty factor
e+ source	6	x 0.8	**4.8**	Slightly lower because of Less duty factor
Damping Ring	10	x 1.0	**21**	Assuming similar with DR+RTML combined
RTML	11			
Main Linac	50	x 1.8 x 1.5 (~ x 3 x 2)	**113** **(~ 300)**	Assuming twin cavity in common CM (x1.5), and 2/3 Gradient resulting x1.5 length, Depending on the HOM absorption temperature and periodicity, and cavity frequency
BDS	7	x 1.8	**13**	Doubling # of BDS lines necessary, with less requirement after collision,
IR	4	x 1	**4**	Assuming similar IR design
Main Dump	1	x 0.1	**0.1**	Assuming abort-dump remaining
Common	7	x 1.5 ~ x 3	**11** **~ 21**	Assuming it ~ proportional to ML length, and Assuming more cost for twin ML w/ additional work.
Total	100		**≥ 170** **(~ 370)**	Depending on the ERL design: HOM absorption T. and Frequency

An Exercise: Relative Cost Estimates of ERLC compared with ILC

		ERLC As proposed 1.3 GHz HOM to 1.8K~	ERLC Re-evaluated 1.3 GHz HOM to 1.8K~	ERLC Re-evaluated 1.3 GHz HOM to 50K ~	ERLC Re-evaluated 1.3 GHz HOM to 80K ~	ERLC Re-evaluated 0.65 GHz HOM to 1.8K ~	ERLC Re-evaluated 0.65 GHz HOM to 50K ~		ILC 1.3 GHz HOM to 2K ~
AC (wall-plug) Power	(MW	(167)	(1686+6)	(490+6)	(415+6)	(683+6)	(384+6)		(110)
Sources	%	**8**	**8**	**8**	**8**	**8**	**8**		**10**
Wiggler/DR + RTML	%	21	21	21	21	**21**	**21**		21
Main Linac	%	50x1.5x1.5	50x3x2	50x2x1.5	50x2x2	50x3x1.5	50x3x2		50
BDS	%	13	13	13	13				7
IR	%	4	4	4	4	4	4		4
Main Dump	%	-	-	-	-	-	-		1
Common	%	11	21	14	14	14	14		7
Grand total	**%**	**170**	**367**	**235**	**260**	**272**	**347**		**100**
Note:		Respecting original estimate	Cryogenics load very high	Cryogenics load reduced	.Cryogenics load reduced, Additional ML length required for many HOM absorber	SRF frequency reduced and CM cost high (x3) (Referring SPL-CM)	SRF frequency reduced and CM cost high (x3) Additional tunnel length.		

Outline

- General Comparisons
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- Further questions and issues to be investigated

Questions to be settled

- How relatively expensive is twin aperture SRF cavity?
- How Hom load may be reduced with 650 MHz and higher?
    - How is it practical even in case of twin?
- How HOM load may be effectively extracted to Higher temperature and/or RT with a large fraction?
    - Less multiple cavity?
    - How much distance shall be considered b/w CM?
        - How much reduced in filling factor → 50 % or less ?
        - A suggested guideline : Cornel ER-MLC, CBETA
- RF Phase accuracy/tolerance to sufficiently match to both acceleration and deceleration (in opposite direction)

Many Thanks for Eiji's and Chris' comments, advices & references !

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 103501 (2017)

Experimental studies of 7-cell dual axis asymmetric cavity for energy recovery linac

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(Received 28 May 2017; pu

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 083502 (2016)

Asymmetric dual axis energy recovery linac for ultrahigh flux sources of coherent x-ray and THz radiation: Investigations towards its ultimate performance

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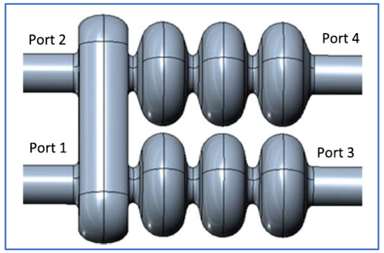

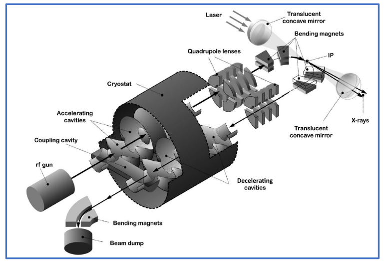

MOPO016 Proceedings of SRF2011, Chicago, IL USA

SUPERCONDUCTING RF FOR THE CORNELL ENERGY-RECOVERY-LINAC MAIN LINAC *

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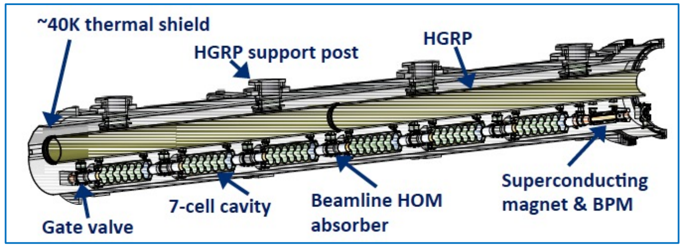
BNL-114549-2017-IR
CBETA/015b
June 2017



Courtesy: B. Rimmer

HOM damping at ambient temperature

MOPP140 Proceedings of EPAC08, Genoa, Italy

STATUS AND TEST RESULTS OF HIGH CURRENT 5-CELL SRF CAVITIES DEVELOPED AT JLAB*

F. Marhauser#, W. Clemens, G. Cheng, G. Ciovati, E.F. Daly, D. Forehand, J. Henry, P. Kneisel, S. Manning, R. Manus, R.A. Rimmer, C. Tennant, H. Wang,
Jefferson Laboratory, Newport News, VA 23606, U.S.A.

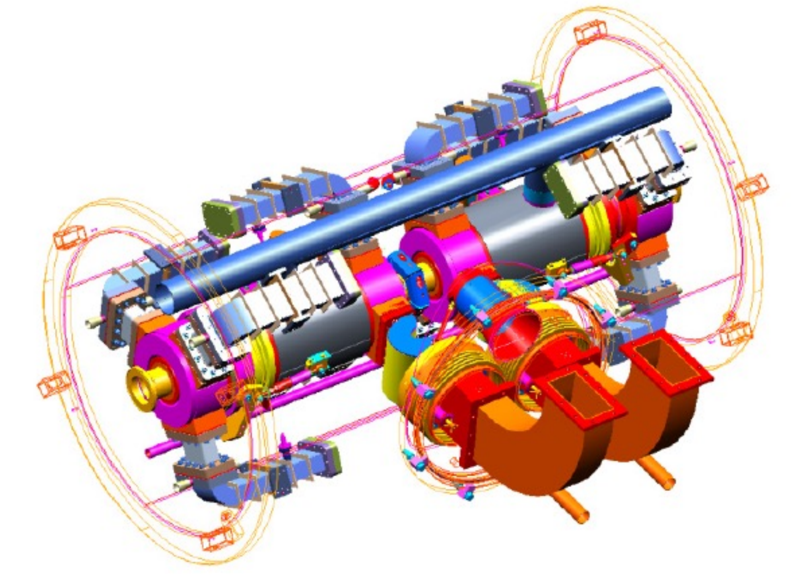


Figure 1: 3D CAD view inside a 1497 MHz high-current cavity pair cryomodule under development.

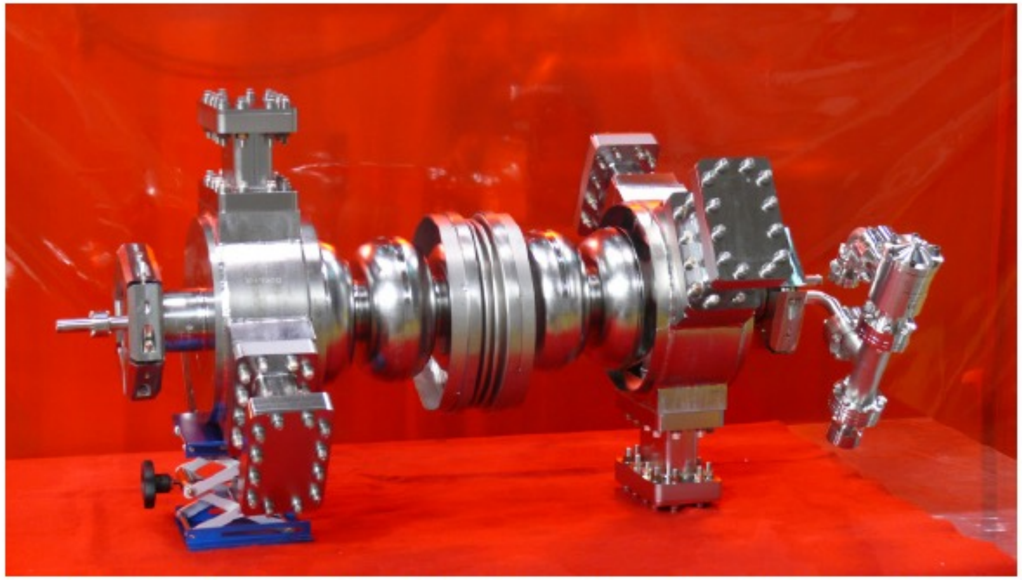


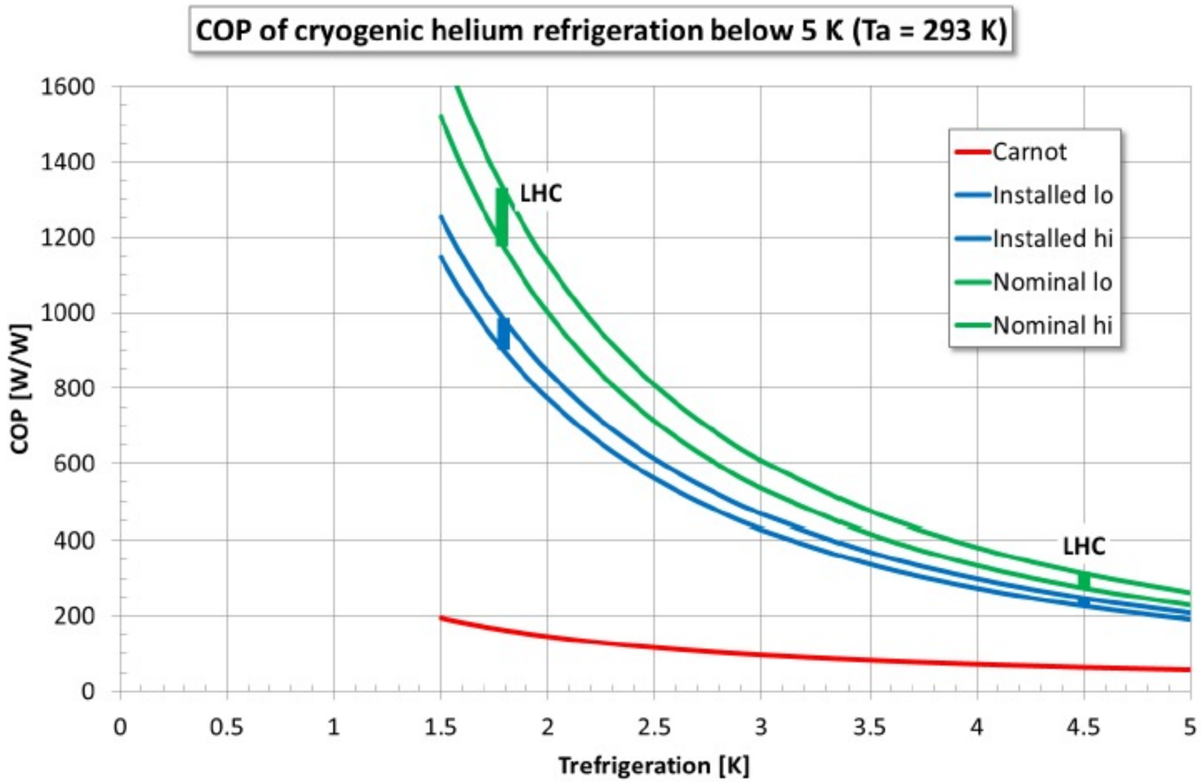
Figure 2: 1.5 GHz high-current cavity with two three-folded waveguides and blanked-off Nb extensions.

Overview -- again

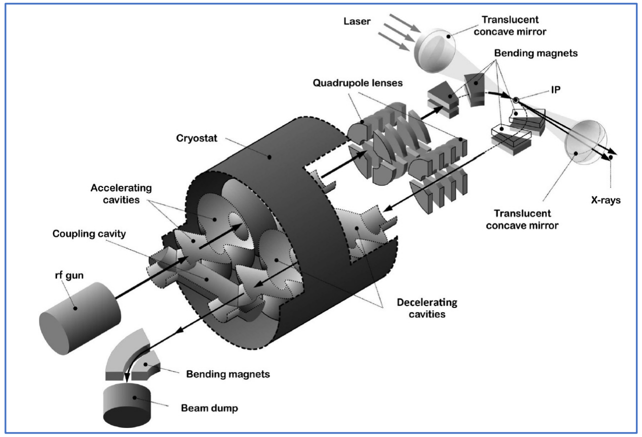
- ERLC requires **significant AC (wall-plug) power** consumption mainly for cryogenics loaded by RF dynamic loss because of RF voltage and HOM load because of beam current, under CW mode, even though the duty factor limited to 1/3. It is un-acceptably high, if the CM and HOM absorption design as similar as that of ILC.
- To significantly reduce the AC power, ERLC-CM designs needs to be based on:
  - Efficient CM design with **twin aperture SRF cavities** in common Cryomodules,
  - **HOM loads extracted** directly to much higher temperature (~50 ~ 100K)
    - HOM absorber/dumper at **each cavity end** (instead of each CM end)
  - It results in **longer CM** and and ML lengths, and additional cost.
- The design with **reduced N per bunch** (and/or **increased bunch distance**) and a **full CW mode** (DF=1) remains as a possibility for the proposal to be more practical, with the **luminosity** to be reasonably **compromised**.
- The construction **cost** would be relatively **much higher** than that estimated to ILC.
- **Long term development** will be necessary to demonstrate and establish the technology for the project realization: twin aperture cavity, frequent HOM load extraction, thermal & cryogenics design optimization, and others.

Appendix

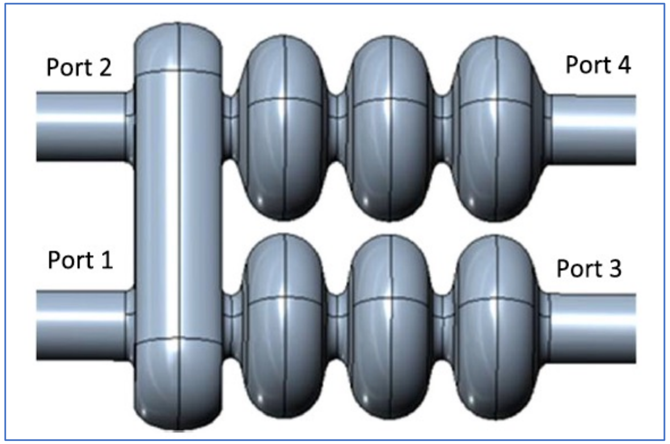
Cryogenic refrigeration
Efficiency degrades at reduced capacity



Courtesy: C. Adolphsen



R. Ainsworth et al., “Asymmetric dual axis ERL ,,”
PRAB 19, 083502 (2016)



I.V. Konoplev et al.,
"Experimental studies of 7-cell dual axis asymmetric cavity …”
PRAB, 20 103501 (2017)

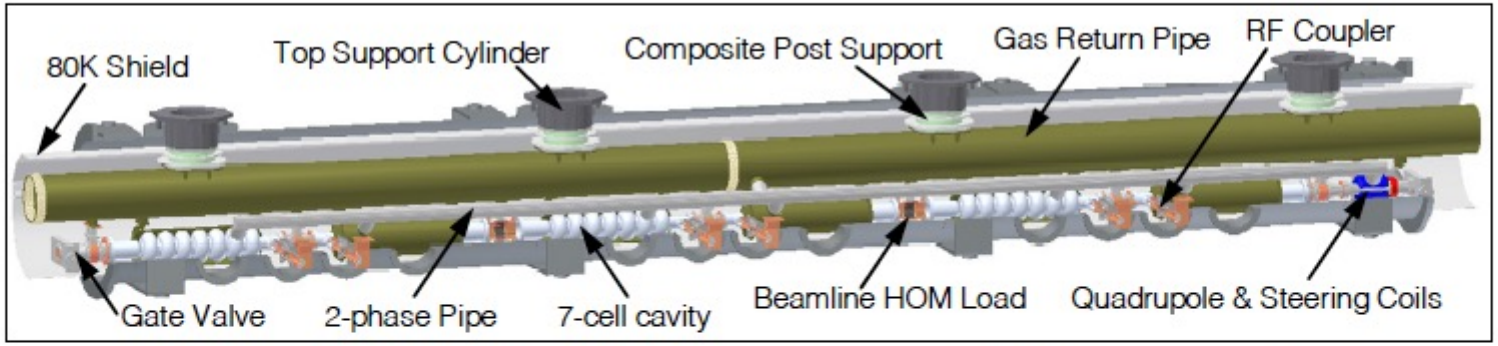
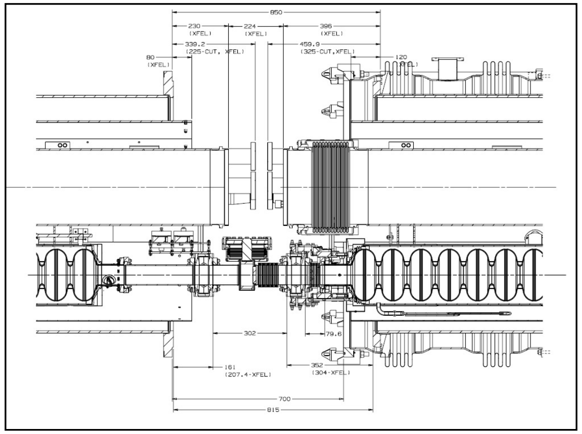
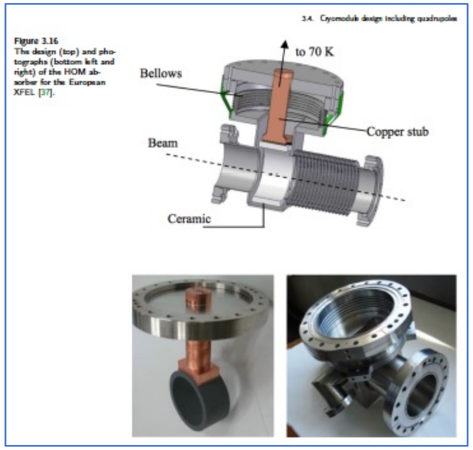


Figure 1: A cut-away CAD model showing the main features of the ERL Linac cryomodule.

"Cryogenic heat load of the Cornell ERL Main Lincac Cryomodule"
E. Chojnnacki et al., SRF2009, Berlin, THPPO034.





ILC CM Interconnect, and HOM Absorber

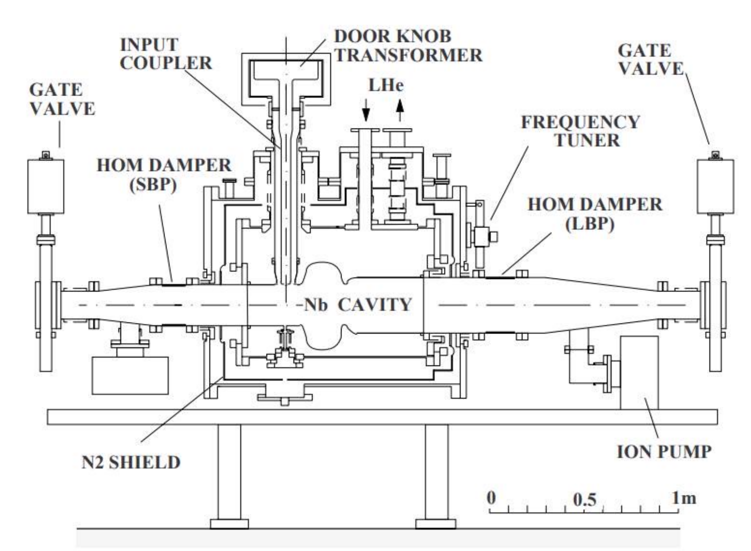
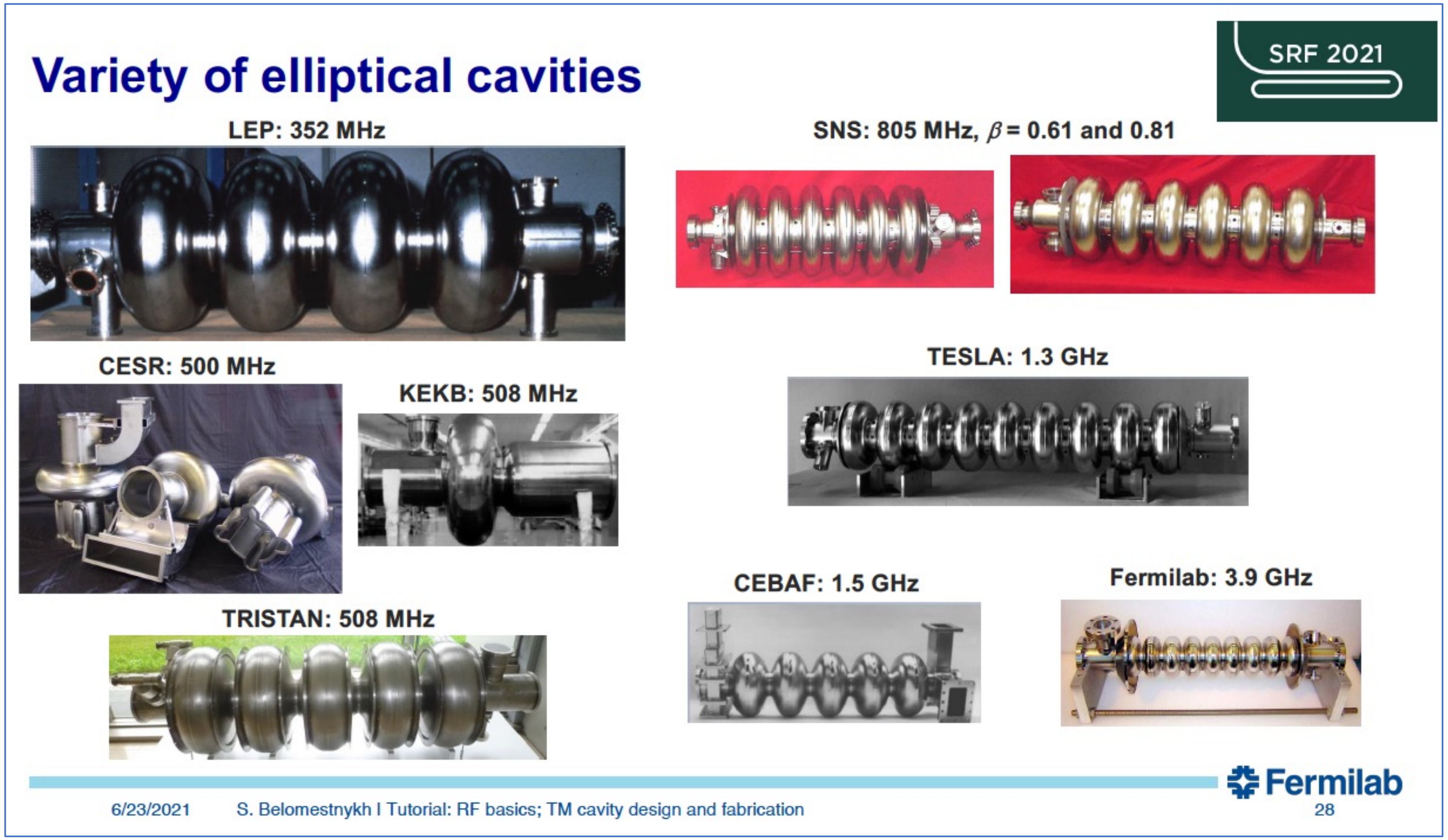


Figure 2: A sectional view of the SC damped cavity.

KEKB Single Cell Cavity
and HOM dumper at RT

Sergey Belomestnkh

Variety of Elliptical Cavities



General Cost Estimate ILC-500 and -250

	TDR: ILC500 [B ILCU] (Estimated by GDE)	ILC250 [B ILCU] (Estimated by LCC)
Accelerator Construction: sum	**n/a**	**n/a**
Value: sub-sum	7.98	4.78 ~ 5.26
Tunnel & building	1.46	1.01
Accelerator & utility	6.52	3.77 ~ 4.24
Labor: Human Resource	22.9 M person-hours (13.5 K person-years)	17.2 M person-hours (10.1 K person-years)

http://www.mext.go.jp/component/b_menu/shingi/toushin/__icsFiles/afieldfile/2018/09/20/1409220_2_1.pdf

FIG. 7. Costs of the ILC250 project in ILCU as evaluated by the Linear Collider Collaboration (LCC), converted to JPY and re-evaluated by KEK, and summarised in the MEXT ILC Advisory Panel report, in July, 2018.