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RF Considerations

S. Belomestnykh

Cornell University

- **Initial parameters**
- **Frequency choice**
- **Optimum gradient**
- **HOM power**
- **Beam loading**
- **Multi-bunch instabilities**
- **Operating issues**
- **RF parameters**
- **Conclusions**

Initial parameters[1]

Total beam current	**25.04 mA**
Energy loss per turn DU	**3990 MeV/turn**
Beam power to SR	**100 MW**
RF frequency	**400 MHz**
Total RF voltage	**4660 MV**
RF cell length	**0.375 m**
SC material	**Nb/Cu**
R/Q per cell	**116 Ohm**

Inherent advantages of Nb/Cu cavities[2]:

- much better thermal stability against quenching
- savings on Nb material
- insensitivity to small magnetic fields
- higher quality factor

Frequency choice

- advantage of operating at 4.5 K → simpler cryostat design; cheaper, more reliable and simpler refrigerator components
- availability of high average power klystrons
- frequency range 300 – 500 MHz

Superconducting RF systems

Parameter		LEP	LHC	SOLEIL	CESR	KEK-B (HER)
I beam tot	[mA]	6	560 (per ring)	500	750	1100
DU	[MeV/turn]	3000		0.7	1.3	3.5
P beam	[MW]	18.2		0.4	0.98	4
f rf	[MHz]	352	400.8	352	500	508.9
V rf tot	[MV]	3500	32	3.8	7.4	17.9
E acc (design)	[MV/m]	7.5 (9)	5.3	5	6 (10)	5
N cell/cav		4	1	1	1	1
Cavity length	[m]	1.702	0.375	0.425	0.3	0.295
N cav		288	16 (8+8)	2	4	8
N cav/cryomodule		4	4	2	1	1
Modular length	[m]	2.553		3.2	2.86	3.7
L active	[m]	490	6	0.9	1.2	2.36
N kly		36		1	4	8
SC material		Nb/Cu	Nb/Cu	Nb/Cu	Nb	Nb
R/Q	[Ohm]	465	89	90	89	93
G - geometry factor	[Ohm]				265.7	252.5
Qo	[10^9]	>3.2 (6 MV/m)	>2 (5 MV/m)	3 (6 MV/m)	1 (6 MV/m)	1
Epk/Eacc		2.3		2	2.5	1.68
Qext		$2x10^6$	var.	$2x10^5$	$2x10^5$	$7x10^4$
Input coupler		Coax	Coax	Coax	WG	Coax
Prf at window	[kW]	80 (500)	176 (500)	200	280 (500)	380 (800)
Static heat leak per cryomodule	[W]	<90	25*	20	30	30
P refr @ 4.5K	[kW]	4x16		0.15	2x0.6	
HOM couplers		Coax	Coax	Coax	Beam-line	Beam-line
k - cryomodule loss factor (s, mm)	[V/pC]	1.76 (13) / 5 (10)		3 (5)	0.48 (13) / 0.6 (10)	1.8 (4)
k tr.	[V/pC/m]	8 (10)				

*without couplers & second beam tube, 2 cavities

Optimum gradient, frequency, temperature

For a large-scale accelerator complex cost optimization determines best accelerating gradient[3]

Cryogenic power

RF losses per unit length increase with square of the gradient:

$$P_m = \frac{E_{acc}^2}{(R/Q)_m \cdot Q_0},$$

where P_m is the RF power per unit length, E_{acc} is the accelerating gradient, $(R/Q)_m$ is the characteristic impedance per unit length, and Q_0 is the quality factor of the cavity.

The total length of the structure is

$$L = \frac{V_{RF}}{E_{acc}},$$

where V_{RF} is the total RF voltage.

Optimum gradient, frequency, temperature (2)

The refrigerator power needed is the sum of the static loss, the fundamental RF loss, HOM induced loss and distribution system loss. To first order the fundamental RF loss is the dominant part. Then the refrigerator power and thus the investment cost is proportional to the accelerating gradient (if Q_0 is independent of gradient):

$$C_{refrigerator} \propto \left(P_m \cdot L\right) \propto E_{acc}$$

We used refrigerator cost factor of 1.7 k\$/W for refrigerator operating at 4.5 K and 3.4 k\$/W for 2.5 K. Also, we took into account quality factor dependence on accelerating gradient as measured for LHC[4] (400 MHz) and LEP[2] (352 MHz) cavities.

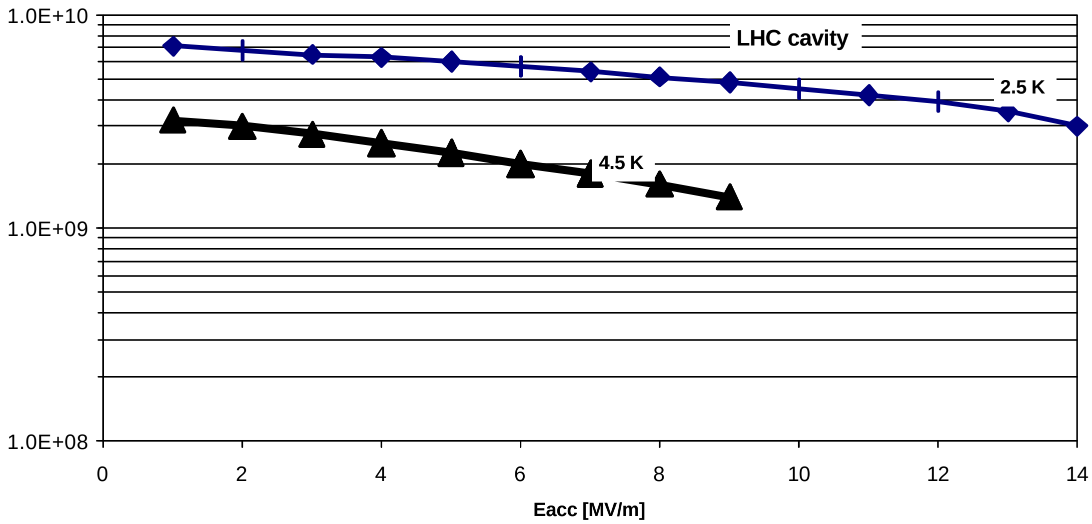
Cryomodule cost

The cryomodule cost scales approximately linearly with total length of the RF structure and thus inversely with the accelerating gradient[5]:

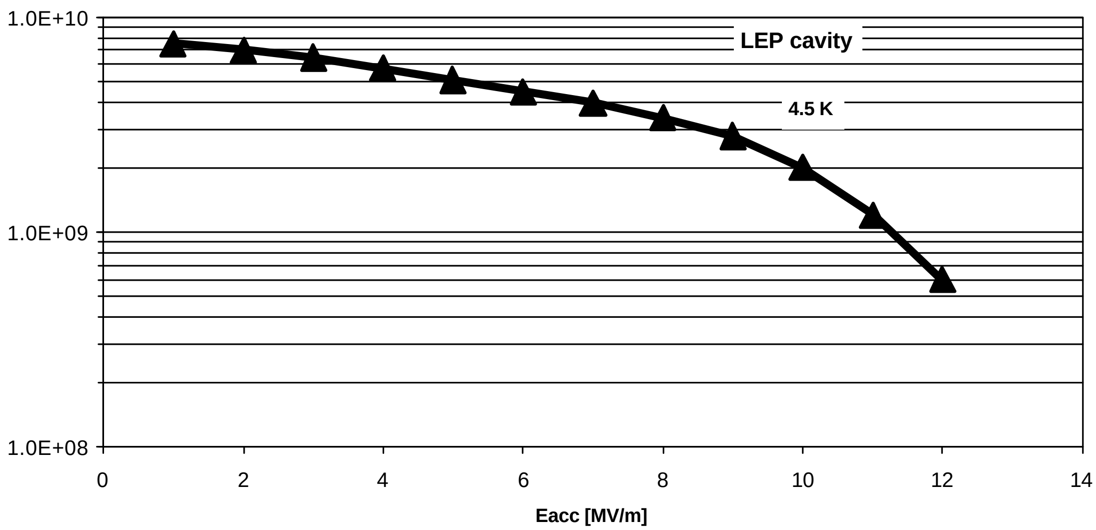
$$C_{cryomodule} \propto (0.8)^{\log(L)} \sqrt{\frac{1300 MHz}{f[MHz]}} \cdot L \propto \frac{1}{E_{acc}}$$

We used cost factor of 200 k\$/m for 4.5 K and 250 k\$/m for 2.5 K.

Q vs. Eacc



Q vs. Eacc



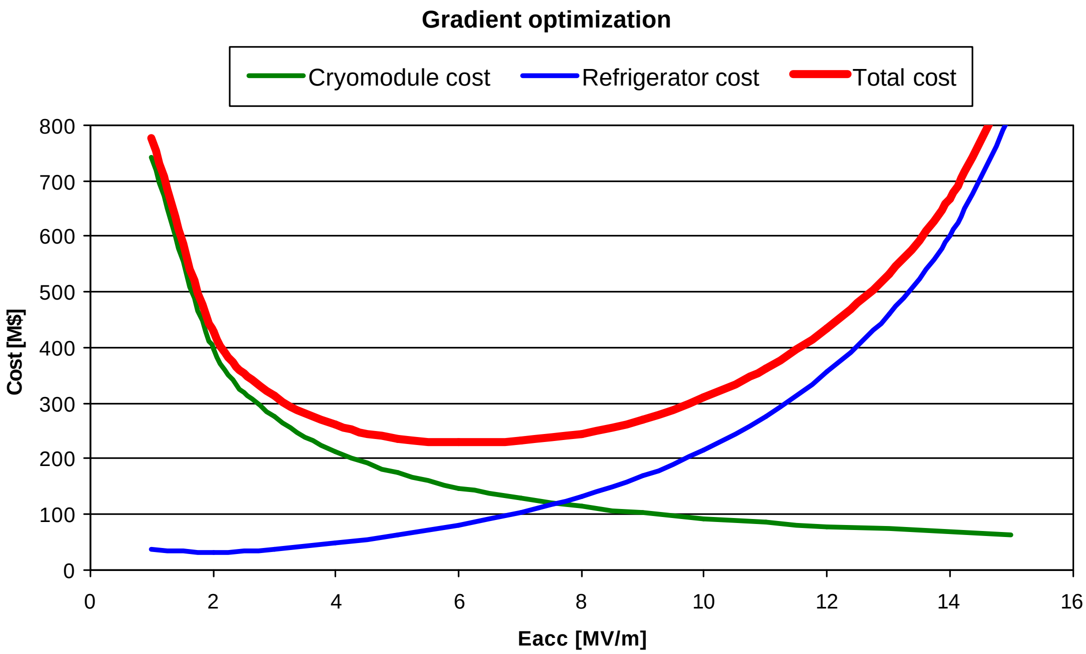
Optimum gradient, frequency, temperature (3)

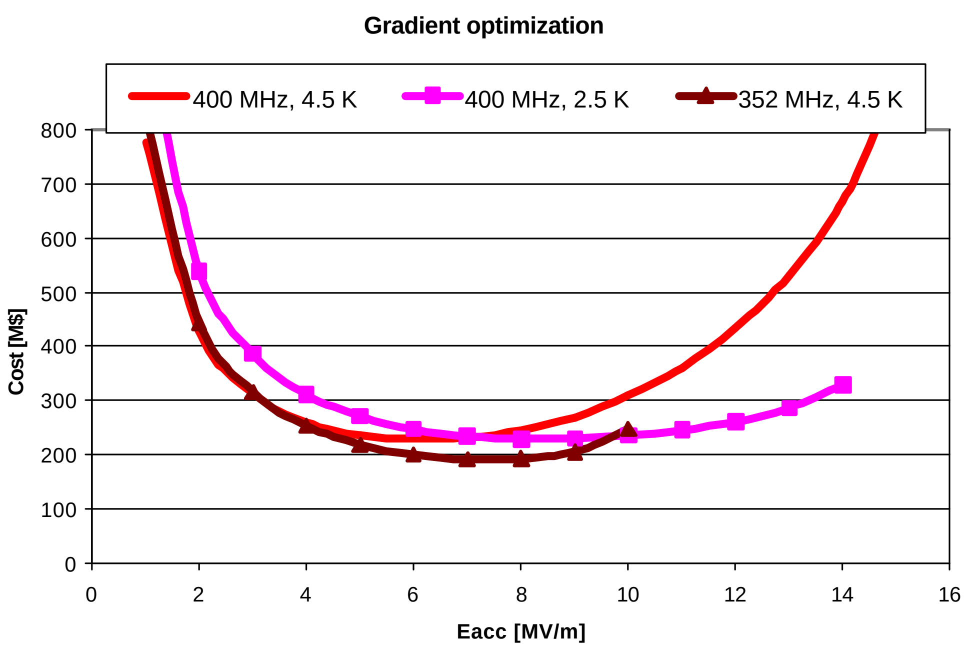
Total cost

The total cost then is dominated by the RF structure cost at low gradients and by cryogenic cost at high gradients. There is a rather broad minimum in the range from 4 to 8 MV/m.

It is worthwhile to see if can gain by operating at lower (2.5 K) temperature or by choosing lower (352 MHz) frequency.

Plots show that lower temperature operation can allow us to use higher gradients and hence fewer number of cryomodules. Choosing lower RF frequency can significantly lower total cost.


Gradient optimization
Cryomodule cost
Refrigerator cost
Total cost
800
700
600
500
400
300
200
100
0
Cost [M$]
0
2
4
6
8
10
12
14
16
Eacc [MV/m]


Gradient optimization
400 MHz, 4.5 K
400 MHz, 2.5 K
352 MHz, 4.5 K
800
700
600
500
400
300
200
100
0
Cost [M$]
0
2
4
6
8
10
12
14
16
Eacc [MV/m]

Optimum gradient, frequency, temperature (4)

For further considerations we chose Eacc = 8 MV/m. (LEP was operating at 7.5 MV/m in 2000).

This determined following parameters:

Ncell = 1552

Ncell/cavity = 4

Ncav/cryomodule = 4
(similar to LEP)

Pcryo = 77.3 kW
(w/o distribution loss and safety margin, but cryo power is dominated by RF losses anyway)

Pbeam/cell = 64.4 kW

Qext = 1.2×10^6

Nkly = 97 (1.3 MW klystrons)

HOM power

Assume LEP cavity shape scaled to 400 MHz: *R*equator = 332 mm, *R*iris = 106 mm. Each cryomodule furnished with two l = 280 mm long tapers to a beam pipe radius of r = 20 mm. To calculate loss factor we used formulae[6,7]:

$$k_{cell} = \frac{1}{2p^2 e_0 R_{iris}}\left(\sqrt{\frac{g}{s}} - 1\right),$$

$$k_{fund} = \frac{w_{fund}(R/Q)_{fund}}{4}\exp\left(-\frac{w^2 s^2}{c^2}\right),$$

$$k_{tapers} = \frac{1}{4p\sqrt{p}e_0 s}\left(1-\tilde{h}_1\right)\ln\frac{R_{iris}}{r},$$

$$\tilde{h}_1 = \min\left(1.0, h_1\right),$$

$$h_1 = \frac{l s}{\left(R_{iris} - r\right)^2},$$

where g is the cavity gap length, s is the bunch length.

HOM power (2)

Then for 7.5 mm bunch length we calculate:

$$k_{\mathrm{cell}} = 0.28 \text{ V/pC}$$

$$k_{\mathrm{fund}} = 0.073 \text{ V/pC}$$

$$k_{\mathrm{parasitic}} = 0.21 \text{ V/pC}$$

$$k_{\mathrm{tapers}} = 0.81 \text{ V/pC}$$

$$\boldsymbol{k_{\mathrm{cryomodule}} = 4.1 \text{ V/pC}}$$

and finally

$$\boldsymbol{P_{\mathrm{HOM}} = 11 \text{ kW/cryomodule}}$$

$$\boldsymbol{P_{\mathrm{HOM}} = 4.26 \text{ MW total}}$$

How much of this power will go to cryogenics? LEP reported cryogenic loss dependence on bunch length, **but** LEP cryomodules had unshielded bellows and lossy HOM cables. HOM dampers will have to be carefully designed. It will probably be a combination of broadband beam line loads (CESR, KEKB-type or LEP-type) to handle high power of propagating HOM and coaxial narrowband probes (LEP) near cavities to load trapped HOM.

Beam loading

Due to small beam current beam loading effects are very mild:

RF phase modulation by the bunched beam

$$\Delta\varphi = \frac{I_b R/Q \cdot h \cdot \sin\varphi_s}{\pi \cdot V_{RF}}$$

(where I_b is the bunch current, h is the RF harmonic number, φ_s is the synchronous phase, and V_{RF} is the RF voltage per cell) is negligibly small (**0.25°**).

Cavity detuning to compensate reactive beam loading

$$\Delta f_r = -\frac{1}{2} f_{RF} \frac{I_0 R/Q \cos\varphi_s}{V_{RF}}$$

(here f_{RF} is the RF frequency, and I_0 is the total beam current) is **100 Hz**, less than cavity bandwidth of 332 Hz.

Beam loading (2)

Special attention must be paid during cavity design period to its mechanical properties:

LEP 4-cell structure has mechanical resonance at approximately 100 Hz. This is very close to synchrotron frequency of 175 Hz and can have very unpleasant effect on beam dynamics. The structure must be stiffened to raise its mechanical resonance frequencies. Also, ponderomotive effects should be studied (LEP RF system suffered from those).

Multi-bunch instabilities

Fundamental mode

Because of low revolution frequency (1.315 kHz) even small detuning of fundamental mode resonant frequency can cause excitation of coupled-bunch mode –1. The growth time due to fundamental mode impedance is **10.2 msec**, shorter than longitudinal damping time of 35 msec. Special feedback loop may be required to deal with this instability[8].

Higher-order modes

We can estimate requirements to loaded *Q* factors for the worst case when high impedance mode (*R/Q* = 20 Ohm) is tuned to the synchrotron sideband:

$$Q_L = \frac{4h \cdot V_{RF} \cos \varphi_s}{\Omega_s \tau_s I_0 m \cdot R/Q}$$

and get $\mathbf{Q_L = 1.6 \times 10^5}$. Here Ω_s is the synchrotron frequency, τ_s is the longitudinal damping time, and *m* is the closest harmonic number to the HOM resonant frequency. This damping is easy to reach. LEP cavities have loaded HOM quality factors of the order of 10^4, which is more than adequate.

Operating issues

As in case of LEP reliability of RF system will be very important issue. **Trip rate** at LEP was **1/(14 minutes)**. In order to avoid frequent beam losses, system must have enough RF voltage margin so that temporary loss of one or two RF stations does not cause a beam dump. LEP had **7%** reserve voltage.

RF parameters

Parameter		**e+e- at VLHC**	**LEP**
I beam total	[mA]	**25.04**	6
ΔU	[MeV/turn]	**3990**	3000
P beam	[MW]	**100**	18.2
f rf	[MHz]	**400**	352
V rf total	[MV]	**4660**	3500
E acc	[MV/m]	**8**	7.5
N cell/cavity		**4**	4
Cavity length	[m]	**1.5**	1.702
N cav		**388**	288
N cav/cryomodule		**4**	4
Modular length	[m]	**12**	2.553/12.5
L active	[m]	**582.5**	490
N kly		**97**	36
SC material		**Nb/Cu**	Nb/Cu
R/Q per cell	[Ohm]	**116**	116
Qo	[10^9]	**1.6 (8 MV/m)**	3.2 (6 MV/m)
Qext		**1.2´10^6**	2×10^6
Input coupler		**Coax**	Coax
Prf at window	[kW]	**258**	80
Static heat leak	[W]	**84**	90
P refr @ 4.5 K	[kW]	**100**	64

HOM couplers		**Coax**	Coax
k (s, mm)	[V/pC]	**4.1 (7.5)**	5 (10)

Referencies

[1] T. Sen and J. Norem, "A Very Large Lepton Collider in the VLHC tunnel," February 8, 2001.

[2] D. Boussard, "Performance of the LEP2 SRF System," *Proc. of the PAC'97*, pp. 2879-2883.

[3] D. Proch, "Superconducting cavities for accelerators," *Rep. Prog. Phys.* **61** (1998) 431-482.

[4] S. Bauer et al., "Production of Nb/Cu Sputtered Superconducting Cavities for LHC," *Proc. of the 9th SRF Workshop*.

[5] H. Padamsee, "SRF for Muon Colliders," *Proc. of the 9th SRF Workshop*.

[6] A.V. Novokhatski, "On the estimation of the wake potential for an ultrarelativistic charge in an accelerating structure," Preprint INP 88-39.

[7] S.A. Heifets and S.A. Kheifets, "Coupling impedance in modern accelerators," *Rev. Mod. Phys*. **63** (1991) 631-673.

[8] F. Pedersen, "RF Cavity Feedback," *Proc. of the "B-Factories: The State of the Art in Accelerators, Detectors and Physics,"* pp. 192-207