ELECTRICAL POWER BUDGET FOR FCC-ee*

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Abstract

We present a first rough estimate for the electrical power consumption of the FCC-ee lepton collider [1, 2]. This electrical power is dominated by the RF system, which provides the motivation for the ongoing R&D on highly efficient RF power sources. Other contributions come from the warm arc magnets, the cryogenics systems, cooling, ventilation, general services, the particle-physics detectors, and the injector complex.

INTRODUCTION

The electrical power consumption is a critical design parameter of future highest-energy circular lepton colliders, such as the FCC-ee [1, 2].

Some rough estimates of power budgets have been made in the past for an FCC-ee precursor called TLEP [3, 4, 5].

Another reference is LEP. The total power of the 1998 CERN complex was 237 MW. Of these only 1 MW was for the injector complex (LIL and EPA at 0.5 GeV), 12 MW for the PS (3.5 GeV), 52 MW for the SPS (22 GeV; both SPS and PS were also operating for other users, at higher energies), and up to 120 MW for LEP operation itself [6]. The average power consumption of LEP2 in its last year of operation provides further details and energy-consumption values for the various LEP2 sub-systems [7].

The FCC lepton collider, FCC-ee, is based on a constant value of synchrotron radiation power equal to 100 MW. The compensation of this loss power is accomplished by the radiofrequency (RF) system, which converts electrical wall-plug power to RF power in the accelerating cavities. Superconducting cavities operating in continuous wave mode transform RF power to beam power with basically 100% efficiency, since the beam extracts the RF power many orders of magnitude faster than the wall losses, given the high Q value of the superconducting cavities.

RF SYSTEM

Various energy-dependent configurations for the FCC-ee SRF system were discussed at a recent review [8]. In the following we consider one example, which is similar to a proposal by R. Calaga [9].

Two different modes of operation can be distinguished. At low energy (especially for running at the Z pole), the beam current is high, and the RF voltage low, so that a moderate number of cavities will suffice. At higher energy (especially for Higgs and top mode) the beam current is low, and the RF voltage high. Many cavities with reduced power per cavity are required.

Single-cell cavities are preferred for operation at high beam current, in particular at the Z pole. Multi-cell cavities may be advantageous at the higher energies with lower current. An RF frequency of 400 MHz is chosen, i.e. the same as for the FCC-hh hadron collider. As a concrete example we consider thin-film-niobium on copper cavities, operated at a temperature of 4.5 K, a technology which was successfully developed for LEP2.

LEP2 employed 288 4-cell 352-MHz Nb/Cu cavities operated at 4.5 K, which achieved an average gradient of 7.5 MV/m (with a spread ranging from 6 to 9 MV/m) [10]. At a gradient of 7 MV/m an average Q value of 3.1×10^9 was measured in the LEP2 cavity reception tests [11], the best cavities showing Q values around 5×10^9. As a realistic R&D target for FCC-ee we consider 2-cell Nb/Cu cavities with a Q of 3×10^9 at a gradient of 10 MV/m, which is not far from the performance of the best LEP2 cavities; similar values could also be expected from bulk Nb cavities at 4.5 K and 400 MHz. In the long term, the Nb/Cu cavities could potentially be replaced by either Nb_3Sn/Nb cavities or Nb_3Sn/Cu cavities, also at 4.5 K, with Q values above 8×10^9 [12]. but we do not rely on such advance.

Concerning RF power sources, a recent breakthrough in klystron design promises 90% efficiency [13]. We assume that the actual device may achieve 85% peak performance.

Due to the nonlinear saturation of the klystron output the active RF feedback requires a margin. Therefore, for high-current operation at 45.6 GeV beam the klystrons are taken to be operated some 20% below their peak efficiency. We adopt the same margin for 80 GeV. We assume that the klystron margin can be reduced to 10% for the much lower current operation in ZH production and at the $t\bar{t}$ threshold. LEP2 klystrons even operated in saturation [5, 14].

For all energies, RF power distribution losses of 5% are considered. In addition, the electrical AC/DC power converter losses are taken to be 5% [4, 5].

Instead of klystrons, for the high energies there also exists the option to power individual cavities with inductive output tubes (IOTs) or solid-state amplifiers (SSAs). The peak efficiency of these devices is presently around 65%. This is significantly less than our target value for the klystrons. However, IOTs and SSAs have a more linear output behaviour than klystrons, and, therefore, less, or no, degradation would be implied by active feedback.

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Table 1: Tentative example RF parameters of FCC-ee for different energies and comparison with LEP2.

	Z		W	ZH	$t\bar{t}$	LEP2
beam energy [GeV]	45.6		80	120	175	104.5
beam current [mA]	1450		152	30	6.6	3
total SR power [MW]	100		100	100	100	23
SR energy loss / turn [GeV]	0.03		0.33	1.67	7.55	3.34
bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	1.4
number of bunches / beam	30180	91500	5260	780	81	4
rms bunch length in collision [mm]	6.7	3.8	3.1	2.4	2.5	11.5
RF frequency [MHz]	400		400	400	400	352
total voltage [GV]	0.4	0.2	0.8	3.0	10	3.5
number of beams / cavity	1		1	1	2 (shared)	1
number of cavities / beam	150	75	150	400	670 ($\times$2)	288
cells / cavity	1		2	2	2	4
cavity length $l_{\rm cav}$ [m]	0.38		0.75	0.75	0.75	1.7
gradient $E_{\rm acc}$ [MV/m]	7.0		7.1	10	10	6–7
voltage / cavity [MV]	2.7		5.3	7.5	7.5	12
unloaded Q [10^9]	3		3	3	3	>3
power / cavity [MW]	0.33	0.67	0.33	0.125	0.075	~0.12
power source	klystron		klystron	klystron or IOT?		klystron
static cryo wall power [MW]	1.1	0.6	1	3	6	1.5
dynamic cryo wall power [MW]	2	1	4	20	33	5.5
cryo power at RT / cavity [kW]	10		16	29	29	24
total cryo power [MW]	3	2	5	23	39	7
HOM loss / cavity [kW]	<9	3.1	1.2	0.3	0.3	<2

CRYOGENICS SYSTEM

The static losses in the FCC-ee cavity cryomodules are taken to be 5 W/m [15]. For comparison, the LEP cryomodules exhibited static losses close to 8 W/m, while the static losses for the LHC dipole-magnet cryostats are only 0.21 W/m. In addition to the cavity active length we assume that the cryomodule includes a cut-off tube of 1.5 m on either side. The total length of a single-cavity cryomodule will then be about 3.5 or 4 m for 1-cell and 2-cell cavities, respectively. For comparison, a LEP2 cryomodule was 12 m long and contained four 4-cell cavities.

The dynamic heat load is

$$P_{\rm dyn} = \frac{1}{(R/Q)_{\rm lin} Q} \frac{V_{\rm tot}}{E_{\rm acc}} E_{\rm acc}^2 l_{\rm cav} \ , \qquad (1)$$

where $(R/Q)_{\rm lin}$ denotes the "R over Q" value of the cavity (linac definition) in units of Ω, $l_{\rm cav}$ the active length of the cavity (equal to $\lambda_{\rm rf}/2$ or $\lambda_{\rm rf}$ for 1-cell and 2-cell cavities, respectively), Q the unloaded Q value, $V_{\rm tot}$ the total accelerating voltage (per beam), $E_{\rm acc}$ the accelerating gradient in V/m, and $f_{\rm rf}$ the RF frequency.

We consider 1- and 2-cell cavities of thin-film niobium on copper, operated at 4.5 K, with $Q \approx 3\times 10^9$ for field gradients $E_{\rm acc}$ between 7 and 10 MV/m, and $f_{\rm rf} = 400$ MHz. The actual cryogenic load also depends on the cavity R/Q value (assumed as 87 Ω for 1-cell, and 169 Ω for 2-cell cavities; linac definition).

The cryogenics cooling efficiency is obtained as the product of Carnot efficiency (1.5%, at 4.5 K) and technical efficiency (assumed as 30%): about 220 W wall plug power are needed to remove 1 W at 4.5 K.

Table 1 lists example cavity parameters for different modes of operation, including HOM power (to be absorbed at room temperature) and total refrigerator power, and compares these with the values of LEP2 [14]. The FCC-ee HOM losses were computed by O. Brunner [16].

WARM MAGNETS

The warm magnets of the arcs are the other big consumers of electrical power. Assuming the same current density on the conductor, the power of the dipoles (quadrupoles) increases linearly (quadratically) with the aperture. In both cases, the power depends quadratically on the beam energy. For a fixed integrated gradient, the quadrupole power scales with the inverse magnet length.

The FCC-ee dipole magnets should provide a rather low field of about 0.05 T at the $t\bar{t}$ energy (and even lower fields at lower energies). Both dipole and quadrupole magnets are conceived as twin-aperture designs with a common central coil to minimize construction cost, magnet size, and electrical power [17]. With a vertical gap of 90 mm and assuming aluminium busbars, the total dipole-magnet power at the top energy (175 GeV/beam) is about 10 MW (plus 20–30% for losses in interconnects and cables). The FODO-lattice

Table 2: Target values for average power per subsystem in different operation modes of FCC-ee, compared with the average power of LEP2 (computed, for each system, as total energy consumed in the year 2000 [7] divided by 200 days).

lepton collider	Z		W	ZH	$t\bar{t}$	LEP2
luminosity / interaction point [10^{34} cm^{-2}s^{-1}]	207	90	19	5	1.3	0.012
total RF power [MW]	163		163	145	145	42
collider cryogenics [MW]	3	2	5	23	39	18
collider magnets [MW]	3		10	24	50	16
booster RF & cryogenics [MW]	4		4	6	7	N/A
booster magnets [MW]	0		1	2	5	N/A
pre-injector complex [MW]	10		10	10	10	10
physics detectors (2) [MW]	10		10	10	10	9
cooling & ventilation [MW]	47		49	52	62	16
general services [MW]	36		36	36	36	9
total electrical power [MW]	276	∼275	∼288	∼308	∼364	∼120

quadrupoles tend to require more power than the dipoles. With a magnet length of 3.5 m the quadrupole field gradient at the $t\bar{t}$ energy (175 GeV/beam) is 8.8 T/m. Considering copper conductor and an inner diameter of 88 mm the total power required for all arc quadrupoles of both beams is expected to stay below 25 MW (at 175 GeV).

About 10 MW is allocated for the magnets of the straight sections. This value will be refined once individual magnet designs for the final foci and other insertions are available.

Leaving a margin and including converter losses we estimate a total power consumption of 50 MW for all collider magnet systems, at 175 GeV.

COOLING AND VENTILATION

At LEP the electrical power for cooling and ventilation amounted to about 13% of the total power consumption [7]. For FCC-ee we tentatively allocate a higher fraction, around 17%, of the spent power for cooling and ventilation, which includes the removal of the heat from arc synchrotron radiation. This number is still quite uncertain at the present stage. The extraction of heat from the RF sections may require additional containment and cooling circuits, in view of 20–30 MW of heat load (from the RF system) expected for each of the two 4-km long straights [18].

GENERAL SERVICES

The general services for LEP consumed about 9 MW on average. With an almost 4 times larger machine we linearly increase the related power to 36 MW. This might be pessimistic, since for FCC-ee we consider 2 collision points, compared with 4 experiments at LEP, and in view of fewer shafts per unit length. On the other hand, the FCC-ee access shafts are deeper and the arc sections are longer.

INJECTOR COMPLEX

The LEP injector complex together with the PS at 3.5 GeV required 13 MW power [6]. The SuperKEKB injector complex uses about 5 MW for gun and linac plus 3–4 MW for the damping ring [19], or a total of 8–9 MW. The SuperKEKB complex can deliver the intensities required for FCC-ee. We consider 10 MW a good estimate for the average power of the FCC-ee pre-injector complex.

As for the top-up booster, its average power values for the RF system, for cryogenics, and for the warm magnets are much lower than for the collider, since (1) the booster is cycling, (2) the charge per bunch and number of bunches accelerated are only a small fraction of the full beam charge in the collider, and (3) only, at most, one beam is present in the booster. More accurate estimates can be made when the exact cycles of the injector complex have been defined.

DETECTORS

The average energy consumption of two LEP detectors, L3 and OPAL, was about 9 MW in total [7]. The present CMS detector at the LHC consumes 4.2 MW [20]. For the two FCC-ee experiments, we assume a comparable power level, of 5 MW each.

CONCLUSIONS

Compiling our estimates, Table 2 gives a first idea of target power budgets for the FCC-ee lepton collider in its different modes of operation. Also shown, as a reference, are the corresponding average numbers from the last year of LEP2 operation [7]. The total power for the $t\bar{t}$ collider of about 364 MW is similar to the estimate of 359 MW given by M. Ross [4], though values for individual sub-systems differ, in some cases substantially.

The FCC-ee luminosity can be varied by changing the number of bunches, keeping the luminosity per bunch constant. A large portion of Table 2 varies approximately linearly with the beam current, and hence about linearly with the luminosity. Therefore, e.g., a factor two lower luminosity would lower the total power by about a factor of two.

The contents of this paper represents work in progress, and uncertainties may be of order ±30%.

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