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FCC-ee OPERATION MODEL, AVAILABILITY & PERFORMANCE*

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Abstract

This document discusses the machine parameters and expected luminosity performance for the proposed future circular lepton collider FCC-ee. Particular emphasis is put on availability, physics run time, and efficiency. Key performance assumptions are compared with the operational experience of several past and present colliders including their injectors — LHC, LEP/LEP-2, PEP-II, KEKB, BEPCII, DAFNE, SLC and the SPS complex.

INTRODUCTION

In the following, we describe the goals and assumptions for the FCC-ee operation plan, and we confront our assumptions with the corresponding statistical information from several similar colliders, especially KEKB and PEP-II.

GOALS, MODES, PARAMETERS

The baseline FCC-ee features four modes of operation: (1) on the Z pole, (2) at the WW threshold, (3) at the HZ production peak, and (4) at the $t\bar{t}$ threshold. Running modes (1)–(3) are combined into a 'phase 1'. Running mode (4) implies a major reconfiguration and is called 'phase 2'.

The physics goals of FCC-ee require the following integrated luminosities for the different operation modes [1, 2], summed over two interaction points (IPs): 150 ab^{-1} at and around the Z pole (88, 91, 94 GeV centre-of-mass energy); 10 ab^{-1} at the W^+W^- threshold ($\sim$ 161 GeV with a ±few GeV scan); 5 ab^{-1} at the HZ maximum ($\sim$ 240 GeV); 1.5 ab^{-1} at and above the $t\bar{t}$ threshold (a few 100 fb^{-1} with a scan from 340 to 350 GeV, and the remainder at 365 GeV.

FCC-ee machine parameters for all modes of operation are summarized in Table 1.

ESTIMATING ANNUAL PERFORMANCE

The annual luminosity estimates for FCC-ee at each mode of operation are derived from three parameters:

- Nominal luminosity L: taken to be 10–15% lower than the luminosity simulated for the baseline beam parameters. This nominal luminosity is considered from the third year onward in phase 1 (Z pole), and from the second year in phase 2 ($t\bar{t}$ threshold). The luminosity for the first and second year of phase 1 and for the first year of phase 2 are assumed to be smaller, on average, by another factor or two, in order to account for a learning period during initial operation.
- It is assumed that 185 days per year are scheduled for physics. These 185 days are obtained by subtracting from one year (365 days), 17 weeks of extended winter shutdown (120 days), 30 days of annual commissioning, 20 days for machine development, and 11 days for technical stops.
- Nominal luminosity L and time for physics T are converted into integrated luminosity $L_{\rm int}$ via an 'efficiency factor' E, according to

$$L_{\rm int} = ETL\ . \qquad (1)$$

  The efficiency factor E is an empirical factor, whose value can be extrapolated from other similar machines, or by simulations with average failure rate and average downtime. Thanks to the top-up mode of operation, it is expected that E will be about five percent lower than the availability of the collider complex. We assume an availability of at least 80% and, thereby, a corresponding efficiency $E \geq 75\%$.

The assumed 17 weeks of average winter shutdown are longer than the time required for the installation and RF commissioning of new cryomodules (see Table 2 below). Also the 20 days per year allocated for machine development (MD) are higher than the corresponding number for LEP (e.g. in the year 2000 only 5 days of LEP MDs were scheduled [3]).

CONFIGURATIONS AND SHUTDOWNS

The machine operation is expected to start with Z running, similar to LEP-1, as this requires the lowest RF voltage, implying the smallest amount of RF installation and the associated minimum beam impedance.

The changes in the machine configuration required between the Z, W and H running, can be implemented during the successive winter shutdowns.

The length of these FCC-ee winter shutdowns is likely to be dominated by the installation and RF commissioning of new cryomodules in preparing for, or during transition to, the next running modes. Considering only a single cryomodule transport per working day, the minimum total length of the winter shutdown is estimated as

$$n_{\rm working\ days} = n_{\rm cryomodule} + 10 + 10 + 25\ , \qquad (2)$$

where the first 10 days refer to the end of the installation. the second 10 days to the cool down, and the last 25 days to

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Table 1: Key parameters of the FCC-ee circular e^+e^- collider (SR: synchrotron radiation; BS: beamstrahlung)

	Z	W^+W^-	HZ	$t\bar{t}$
Circumference [km]	97.76			
Bending radius [km]	10.76			
Free length to IP l^* [m]	2.2			
SR power / beam [MW]	50			
Beam energy [GeV]	45.6	80	120	182.5
Beam current [mA]	1390	147	29	5.4
Bunches / beam	16640	2000	328	48
Bunch population [10^{11}]	1.7	1.5	1.8	2.3
Horizontal emittance ε_x [nm]	0.27	0.84	0.63	1.46
Vertical emittance ε_y [pm]	1.0	1.7	1.3	2.9
Arc cell phase advances [deg]	60/60		90/90	
Momentum compaction factor α_p [10^{-6}]	14.8		7.3	
Horizontal β_x^* [m]	0.15	0.2	0.3	1.0
Vertical β_y^* [mm]	0.8	1.0	1.0	1.6
Horizontal size at IP σ_x^* [μm]	6.4	13.0	13.7	38.2
Vertical size at IP σ_y^* [nm]	28	41	36	68
Energy spread (SR/BS) σ_δ [%]	0.038/0.132	0.066/0.131	0.099/0.165	0.150/0.192
Bunch length (SR/BS) σ_z [mm]	3.5/12.1	3.0/6.0	3.15/5.3	1.97/2.54
Piwinski angle (SR/BS)	8.2/28.5	3.5/7.0	3.4/5.8	0.8/1.0
RF frequency [MHz]	400	400	400	400 / 800
RF voltage [GV]	0.1	0.75	2.0	4.0 / 6.9
Synchrotron tune Q_s	0.0250	0.0506	0.0358	0.0872
Long. damping time [turns]	1273	236	70.3	20.4
Energy acceptance (DA) [%]	±1.3	±1.3	±1.7	−2.8, +2.4
Luminosity / IP [10^{34}/cm^{-2}s^{-1}]	230	28	8.5	1.55
Beam-beam tune shift ξ_x/ξ_y	0.004/0.133	0.010/0.113	0.016/0.118	0.099/0.126
Lifetime due to radiative Bhabha scattering [min]	68	59	38	39
Lifetime due to beamstrahlung [min]	> 200	> 200	18	18

interlock tests and rf conditioning (5 weeks). These numbers assume that pre-installation work and pre-cabling will be done in advance, i.e. during the previous shutdowns. A minimum of 12 weeks is recommended for the first three shutdowns, even if no, or only few, cryo-modules are installed here. The number of cryomodules to be installed in each winter shutdown is listed in Table 2, along with the resulting minimum lengths of the various shutdowns. From this table, the average length of the winter shutdown would be about 11 weeks, to be compared with an allocated average number of 17 weeks.

The successive winter shutdowns offer an effective time window of about 3 or even 4 months per year for scheduled work in the tunnel. However, longer periods are needed between Higgs and top operation to allow for, in particular, the transverse rearrangement of all (~100) cryomodules and the installation of about 100 new RF cryomodules in the collider and another ~ 100 cryomodules for the booster. The number of cryomodules to be installed or rearranged in this final transition from phase 1 to phase 2 significantly exceeds the amount of work done in a typical LEP winter

Table 2: Minimum lengths of FCC-ee winter shutdowns based on the number of cryomodules (CMs) to be installed and a special 12-week margin for the first three years; shutdown no. 1 refers to the first shutdown after one year of running on the Z pole.

shutdown	no. cryomodules	length of shutdown
shutdown 1	–	12 weeks
shutdown 2	–	12 weeks
shutdown 3	10 CM	12 weeks
shutdown 4	26 CM	20 weeks
shutdown 5	21 CM	14 weeks
shutdown 6	42 CM	18 weeks
shutdown 7	30 CM	15 weeks
shutdown 8	30 CM	15 weeks
long shutdown	104 CM	1 year
shutdown 11	39 CM	17 weeks
shutdown 12	–	–
shutdown 13	–	–
shutdown 14	–	–

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Table 3: Peak luminosity per IP, total luminosity per year (two IPs), luminosity target, and run time for each FCC-ee working point

mode	luminosity $[\mathrm{nb}^{-1}\mathrm{s}^{-1}]$	tot. lumin. $[\mathrm{ab}^{-1}]$ / yr	goal $[\mathrm{ab}^{-1}]$	time [yr]
phase 1				
Z two years	1000	24		2
Z other years	2000	48	150	2
W	250	6	10	1–2
H	70	1.7	5	3
phase 2				
RF reconfiguration				1
$t\bar{t}$ 350 GeV	8	0.20	0.2	1
$t\bar{t}$ 365 GeV	14	0.34	1.5	4

shutdown. For this reason, a one-year shutdown is proposed for this final reconfiguration.

The first year of the phase 2 operation is performed at a beam energy of about 175 GeV, requiring somewhat fewer RF cavities than the later operation at 182.5 GeV.

RUN PARAMETERS AND SCHEDULE

Table 3 presents the nominal luminosity, integrated luminosity per year, physics goals and the resulting running time for the different modes of operation, based on the assumptions laid out above. This yields the time line shown in Fig. 1.

Phase 1 comprises two years of running-in and the full Z pole operation, W threshold scans, and Higgs production modes. It can be accomplished within 8 years. After one additional year of shutdown and staging of the RF, operational phase 2, covering the top quark studies, would last for another 5 years. Therefore, with 185 physics days per year, a physics efficiency of 75%, and the baseline peak luminosities (which are 10% lower than the values reached in simulations), the FCC-ee total run time amounts to 15 years.

The aforementioned assumptions were evoked to arrive at the third and fifth columns of Table 3. We will now scrutinize these assumptions, by comparing with the operational performance of several similar machines.

BENCHMARKING

Achieved Luminosity versus Design Luminosity

LEP was a collider similar to FCC-ee, but operating with only a few bunches and no top-up injection, at significantly lower luminosity. In the first year of LEP-1, with 45.6 GeV beam energy, the current per bunch exceeded the design, the design total current was attained in a single beam, but the total design current in 2 beams was NOT achieved. The peak luminosity in the first year of operation was 50% of design. The vertical beam-beam tune shift (V) was less than 50% of design. The two main reasons why not all the design values could be achieved in the first year were the limitation of the total beam current and the beam-beam tune shift [4]. Looking at the full 12 years of operating LEP [5], the design luminosity was surpassed in 1993 which was the fourth year of operation. LEP-1 achieved 8.4 mA in both beams, higher than the 6 mA design current. It eventually achieved a luminosity of 3.4×10^{31} cm^{-2}s^{-1}, while the design had been 1.6×10^{31}cm^{-2}s^{-1}. However this was accomplished with 8 bunches whereas the design had been for 4 bunches. With the design of 4 bunches per beam LEP never reached the design beam-beam tune shift, mostly due to the lower energy (45.6 GeV) and the correspondingly slower transverse damping (confirmed by beam-beam simulations), while the design energy had been 55 GeV [6] (an energy at which LEP never operated since the Z mass was lower than expected during the design). With the faster transverse damping at higher energy for LEP-2, limitations from the beam-beam effect disappeared. LEP-2 exceeded its design luminosity at 95 GeV (2.7×10^{31}cm^{-2}s^{-1}) within a few months during the first year of operation. It achieved a total beam current of 6.2 mA, and a luminosity of 1×10^{32}cm^{-2}s^{-1}, about 4 times higher than the design [6]. It is interesting that LEP-1 and LEP-2 changed the optics almost every year. At highest energy there was little margin in the LEP RF system. A simultaneous trip of more than two klystrons would lose the beam. The cavity gradients were also pushed to their limits. In 1998 LEP operation, the biggest cause of RF trips was "cavity maximum field" interlocks [7]. Via a number of measures the reliability of the LEP RF system was continually improved so that the impact of RF trips on collider operation became almost unnoticeable [7]. The machine availability of LEP exceeded 85%; in several years it was higher than 90% [3, 8–10].

PEP-II was an asymmetric B factory, colliding a 3.1 GeV positron beam and a 9 GeV electron beams. Beam currents reached 3212 mA for the positrons and 2069 mA for the electrons. The PEP-II design luminosity was 3×10^{33}cm^{-2}s^{-1}, but it ultimately achieved 1.2×10^{34} cm^{-2}s^{-1}. In 2004 PEP-II switched to a top-up injection mode of operation, which significantly increased its integrated daily luminosity. The design integrated luminosity per day had been 130/pb/day. A much higher value of up to 911/pb/day was actually delivered. The top-up mode greatly improved the efficiency, while it did not seem to negatively affect the availability [11]. PEP-II surpassed its design luminosity after 1.5 years of operation, and ultimately reached 4 times the design value [12].

KEKB equally was an asymmetric B factory. It collided 3.5 GeV positrons and 8.0 GeV electrons. Beam currents of 1637 mA (positrons) and 1188 mA (electrons) were reached. The design luminosity was 1.0×10^{34} cm^{-2}s^{-1}. A peak luminosity of 2.11×10^{34} cm^{-2}s^{-1} was achieved. KEKB delivered up to 1.479/fb/day. KEKB, too, operated with continuous top-up injection from the year 2004 onwards. KEKB reached its design luminosity (which was 3 times higher than the design value of PEP-II) 3.5 years after start

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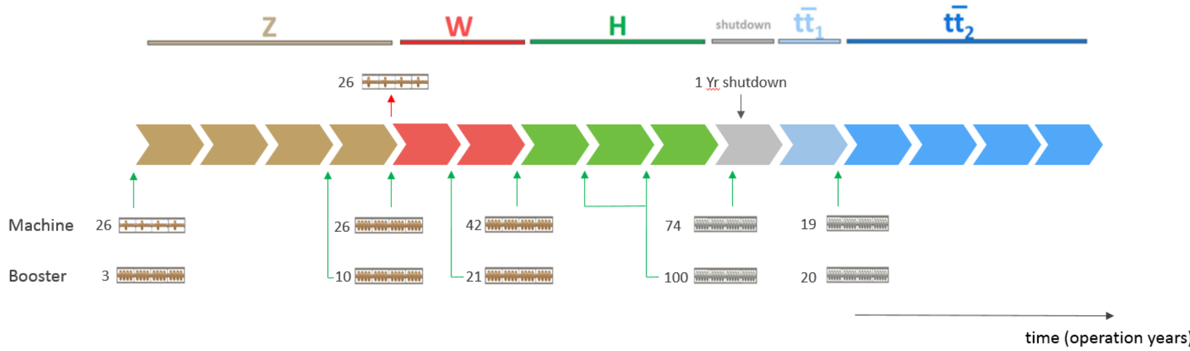

Figure 1: FCC-ee operation time line. The bottom part indicates the number of cryomodules to be installed in the collider and booster, respectively, during the various shutdown periods.

of operation and ultimately exceeded the design luminosity by more than a factor of two [13–15].

Figure 2 shows the daily peak luminosity as a function of day for four consecutive years, 2006–2009. The peak luminosity per day is lower at the start of a run, after longer shut-down periods or hardware interventions, and during periods of beam tuning and machine studies.

From these data we can derive an absolute peak luminosity during a fiscal year, and also an average peak luminosity during a year. These two peak luminosity values are compared in Fig. 3. The difference is of order 30%.

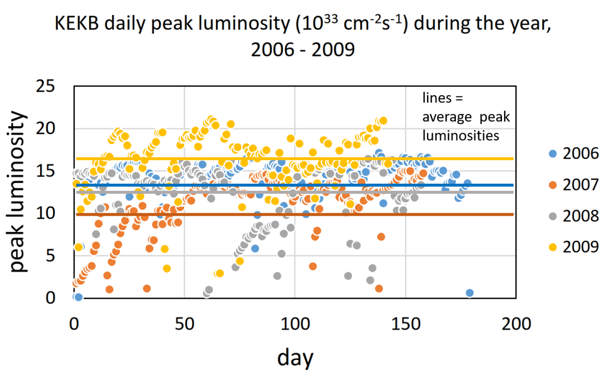

Figure 2: Daily peak luminosity of KEKB as a function of day in the physics run, starting on 1 April, during four consecutive Japanese fiscal years.

BEPCII is a double-ring collider, which runs for high-energy physics (HEP) about 6 months per year, and, in a different configuration, as a light source (BSF) for another two times of 1.5 months, scheduled before and after the HEP run, respectively. The beam energy can be varied from 1.0 to 2.3 GeV. In 2016 BEPCII achieved its design luminosity of 1.0×10^{33} cm^{-2}s^{-1} at 1.89 GeV beam energy, with a current of 850 mA per beam. For the BEPC/BSF synchrotron-radiation operation top up was successfully implemented in November 2015. The availability which on average was already well above 90% increased even further. In 2019 top-up injection will also be implemented for the collider mode of operation.

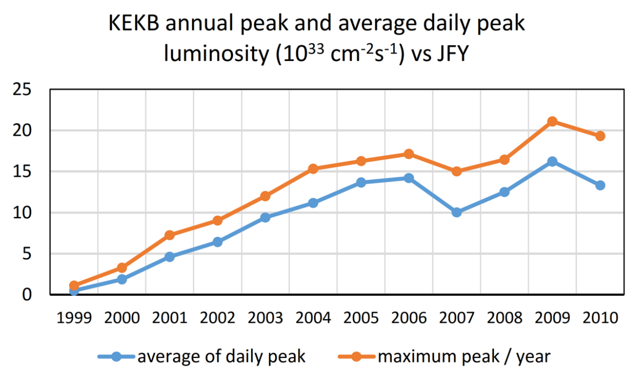

Figure 3: Maximum peak luminosity and average daily peak luminosity of KEKB as a function of Japanese fiscal year.

DAΦNE is an e$^+$e$^-$ double-ring collider, including injection system, which operates at the c.m. energy of the ϕ-meson resonance (1.02 GeV). DAΦNE often changes the particle detector and corresponding IR magnetic-field configuration. DAΦNE achieved 90% of its design maximum luminosity of 5.3×10^{32} cm^{-2}s^{-1} after about 8 years of operation, and after switching to the crab-waist collision scheme. Typical peak currents are 1500–1700 mA for the electrons and 1200 mA for the positrons, the latter limited by electron-cloud effects.

Run Time

Figure 4 compares the annual days of physics running at the aforementioned lepton-positron colliders, for years where data were easily available. The number of 185 days, assumed for FCC-ee, appears like a good average value. It should be noted that the run lengths of the past colliders were often dictated by the availability of financial budget for operation, and not by any technical or schedule constraints. This is true in particular for PEP-II and KEKB. In addition, for PEP-II the 2005 run length was severely reduced by a SLAC lab-wide investigation, review, and remediation of safety concerns, and re-validation of all systems and procedures.

Every year during the winter shutdown LEP prepared for major changes in the configuration (pretzel schemes, bunch trains, installation of sc cavities etc.). Nevertheless in the

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years 1999 and 2000 more than 185 days were scheduled for physics production.

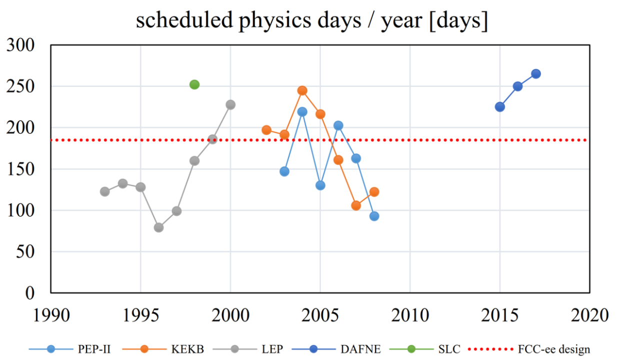

Figure 4: Days of the year dedicated to physics at various past and present e^+e^- colliders.

Availability

Figure 5 shows the availability of the aforementioned lepton-positron colliders, again for the years where data were easily available. All circular e^+e^- colliders operating over the past twenty years (LEP, KEKB, PEP-II, DAΦNE, BEPCII) achieved hardware availabilities well above 80%, and some even above 90%. For KEKB, a degraded availability in the year 2005 was due to technical problems at the BELLE detector, unrelated to the KEKB accelerator. In 2007, the KEKB crab cavities were being commissioned.

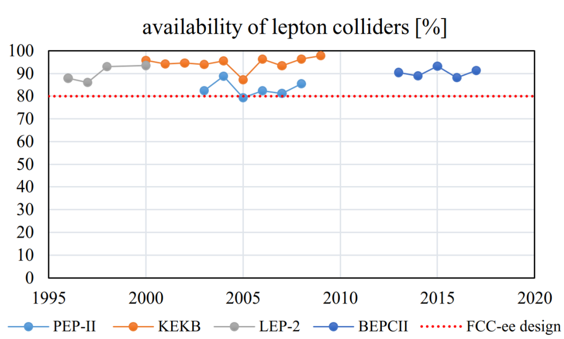

Figure 5: Availability of various past and present e^+e^- colliders.

Through the year 2000, the LEP injector complex (PS and SPS) was operating with proton and ion beams in parallel to LEP e^+e^- operation. Since 1995, the CERN SPS including the entire PS chain delivered beams for physics with an efficiency close to, or above, 80% every year [16], as is illustrated in Fig. 6. The "physics efficiency" of Fig. 6 is a more stringent figure-of-merit than the hardware availability.

The SPS together with the entire PS chain for both proton and ion operation could be argued to be at least of similar complexity as the FCC-ee injector. SPS and PS complex include the proton and ion linacs, the PS booster, LEIR, the PS proper and, of course, the SPS itself, all continually cycled. For comparison, the FCC-ee injector complex comprises a linac, a positron damping ring, a pre-booster, and a main booster, also all cycled. In 2017 and 2018, even the 27 km LHC, with 1600 independent magnet circuits, together with its entire injector chain, has achieved an availability of about 80%. It may also be worth noting that the peak bending fields in the LHC and SPS are 8 and 2 T, respectively, to be contrasted with a peak field of at most 0.05 T in the FCC-ee and its booster.

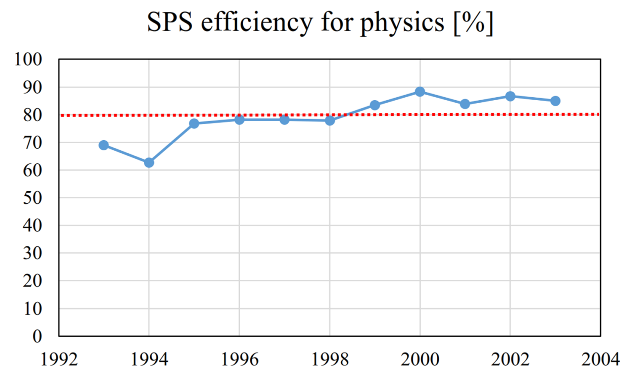

Figure 6: CERN SPS efficiency for physics, including the PS complex [16]. The red dashed line indicates the target availability of FCC-ee.

Efficiency

In the case of FCC-ee, no time is lost for acceleration and the efficiency only reflects the relative downtime due to technical problems and associated re-filling and recovery time. Therefore, the efficiency will be roughly equal to the hardware availability, taken to be at least 80%, minus ∼5% reduction for beam recovery after a failure, assuming (for the Z pole operation) the equivalent of three failures leading to complete beam loss per day on average. For example, after a hardware failure in the collider rings proper, on the Z pole it will take close to 20 minutes (or 1.4% of a day) to refill the collider from zero to nominal beam current. For the higher energy modes of operation the refilling time can be up to ten times shorter.

The assumed efficiency value of 75% with respect to the daily peak luminosity is lower than achieved with top-up injection at KEKB and PEP-II. Figure 7 presents example evolutions over 24 h of beam currents and luminosity, during PEP-II operation with on-energy to-up injection in 2004 and in 2008, respectively. Beam currents and luminosity are constant, except for a few short interruptions due to hardware failures, The performance of KEKB looked quite similar, as is illustrated in Fig. 8, with examples from 2005 and 2009.

Comparing this performance model with LEP operation, the main difference lies in the on-energy top-up injection scheme, without any luminosity decay, and in the implied absence of ramp-down and acceleration.

The value of efficiency depends on the choice of the "nominal luminosity". We can illustrate this with some examples. Several possible choices are plausible. As a first example, in Fig. 9, we present the efficiency of KEKB, PEP-II, LEP

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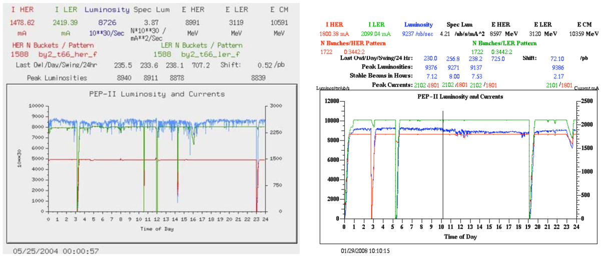

Figure 7: Example evolution of PEP-II beam currents and luminosity in 2004 [17] (left) and 2008 [12] (right). Stored beam current of HER (red curve), LER (green curve), and luminosity (blue curve) of PEP-II over 24 h.

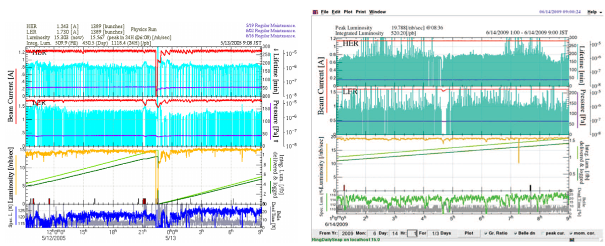

Figure 8: Example evolution of KEKB beam currents and luminosity in 2005 [18] (left) and in 2009 [19] (right). Stored beam current of HER (red line in the top figure), LER (red line in the middle figure), and luminosity (yellow line in the bottom figure) of KEKB over 24 h.

(one year) and SLC (one year), using a "typical" peak luminosity for each year. As a second example, we take the design luminosity value when comuting the efficiency. The result, shown in Fig. 10, is quite different, with efficiency figures reaching values far above 100%. Finally, we can consider the daily (or weekly) peak luminosity and the daily (or weekly) integrated luminosity and from these obtain a daily or weekly) efficiency. Figure 11 presents this daily efficiency of KEKB as a function of day from 1999 to 2010. Histograms for the periods without and with top-up injection, in Figs. 12 and 13, reveal an increase in the most probable efficiency from 57% without top-up to 78% with top-up.

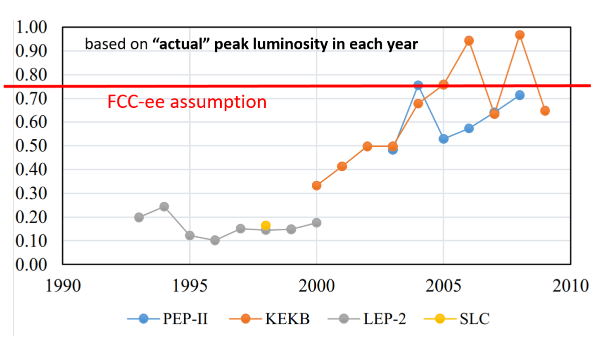

Figure 9: Efficiency calculated from a typical peak luminosity in each year: actual peak in that year (LEP), peak reduced by ∼15% (SLC, PEP-II), average of the daily peak luminosity over the year after removing values below 10% of the peak (KEKB), and design value (well defined, FCC-ee).

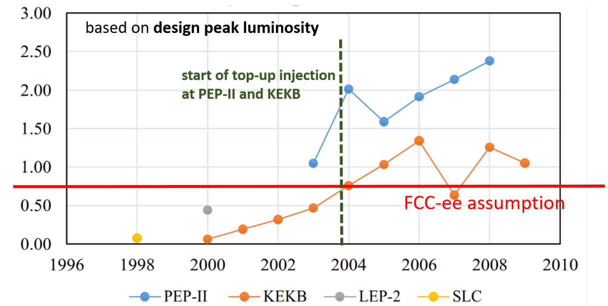

Figure 10: Efficiency calculated from the design luminosity.

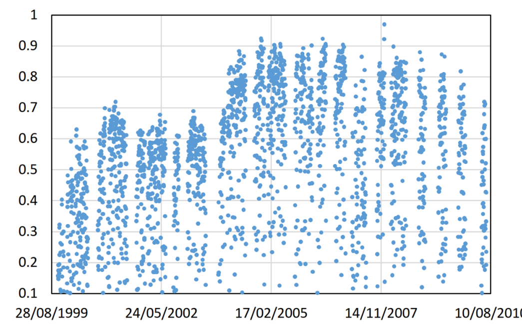

Figure 11: KEKB day-by-day efficiency based on the day-by-day peak and integrated luminosity values.

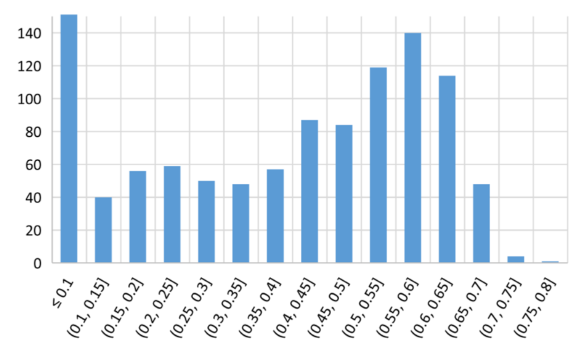

Figure 12: Histogram of KEKB day-by-day efficiency values in units of fraction for the time period without top-up injection, from 1999 to 2003, including shutdowns, technical stops, beam commissioning periods, and machine studies.

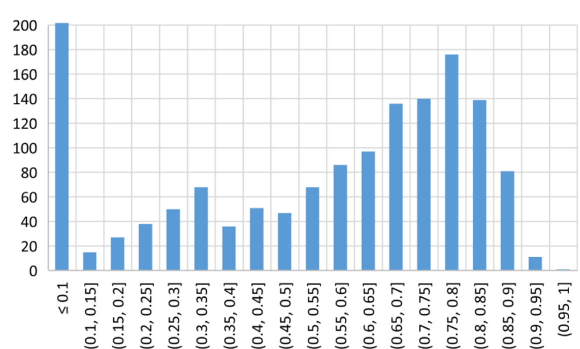

Figure 13: Histogram of KEKB day-by-day efficiency values in units of fraction for the time period with top-up injection, from 2004 to 2010; including shutdowns, technical stops, beam commissioning periods, and machine studies.

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CONCLUSIONS

In summary, the assumed annual physics run time of 185 days, a hardware availability of at least 80%, a corresponding physics efficiency of 75%, and the projected annual luminosities of FCC-ee appear solid, in view of the experience at several circular lepton colliders over the past 30 years. Even surpassing the baseline values for both peak and integrated luminosity appears a realistic possibility (see appendix).

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APPENDIX: BEYOND THE BASELINE

Similar to the experience at LEP/LEP-2, PEP-II, and KEKB, also the FCC-ee could reach luminosity values higher than the design baseline. This could be accomplished as follows:

- The quoted baseline luminosity is conservatively chosen to be 10–15% lower than obtained in simulations.
- Other beam parameter sets, more challenging for the RF system, exist which would allow for higher luminosity.
- The vertical emittance could be pushed down further. The baseline has a small value, but it is far (more than a factor of 10) from the intrinsic limits and features a larger emittance ratio $\varepsilon_y/\varepsilon_x$ than achieved at some of the modern storage-ring light sources.
- The tolerated minimum beam lifetime is longer than what could be supported by the top-up injector complex. Operating with lower lifetime would allow for higher luminosity.
- Assuming two years or one year, respectively, in phase 1 and phase 2 at half the design luminosity could be too pessimistic. LEP-2 and PEP-II reached their design luminosity more quickly.

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