

32. High-Energy Collider Parameters

High-Energy Collider Parameters: e^+e^- Colliders (I)

Table 32.1: Updated in March 2024 with numbers received from representatives of the colliders (contact E. Pianori, LBNL). The table shows the parameter values achieved. Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy; H and V indicate horizontal and vertical directions; s.c. stands for superconducting. Parameters for the defunct SPEAR, DORIS, PETRA, PEP, TRISTAN, and VEPP-2M colliders may be found in our 1996 edition (Phys. Rev. **D54**, 1 July 1996, Part I).

	VEPP-2000 (Novosibirsk)	VEPP-4M (Novosibirsk)	BEPC (China)	BEPC-II (China)	DAΦNE (Frascati)
Physics start date	2010	1994	1989	2008	1999
Physics end date	—	—	2005	—	—
Maximum beam energy (GeV)	1.0	6	2.5	1.89 (2.474 max)	0.510
Delivered integrated luminosity per exp. (fb ⁻¹)	0.25	0.05	0.11	48	≈ 4.7 in 2001-2007 ≈ 2.7 w/crab-waist ≈ 6.8 2014-2018* ≈ 0.4 2021-2022† ≈ 1.1 2023-2024‡
Luminosity (10 ³⁰ cm ⁻² s ⁻¹)	50	20	12.6 at 1.843 GeV 5 at 1.55 GeV	1096	453
Time between collisions (μs)	0.04	0.6	0.8	0.006	0.0027
Full crossing angle (μ rad)	0	0	0	2.2 × 10 ⁴	5 × 10 ⁴
Energy spread (units 10 ⁻³)	0.71	1	0.58 at 2.2 GeV	0.52	0.40
Bunch length (cm)	4	5	≈ 5	1.35	low current: 1 at 15mA: 2
Beam radius (10 ⁻⁶ m)	125 (round)	H:1000 V:30	H:890 V:37	H:347 V:4.5	H:260 V:4.8
Free space at interaction point (m)	±0.5	±2	±2.15	±0.63	±0.295
Luminosity lifetime (hr)	continuous	2	7–12	1.5	0.2
Turn-around time (min)	continuous	18	32	4 (topping up)	2 (topping up)
Injection energy (GeV)	0.2–1.0	1.8	1.55	on energy	on energy
Transverse emittance (10 ⁻⁹ m)	H:150 V:150	H:200 V:20	H:660 V:28	H:121 V:1.56	H:260 V:2.6
β*, amplitude function at interaction point (m)	H:0.05 - 0.11 V:0.05 - 0.11	H:0.75 V:0.05	H:1.2 V:0.05	H:1.0 V:0.0135	H:0.26 V:0.009
Beam-beam tune shift per crossing (units 10 ⁻⁴)	H:850 V:850	500	350	383	440/894 (crab-waist run/test)
RF frequency (MHz)	172	180	199.53	499.8	368.667
Particles per bunch (units 10 ¹⁰)	8	15	20 at 2 GeV 11 at 1.55 GeV	3.8	e ⁻ : 3.2 e ⁺ : 2.1
Bunches per ring per species	1	2	1	119	100 to 110 (120 buckets)
Average beam current per species (mA)	160	80	40 at 2 GeV 22 at 1.55 GeV	910	e ⁻ : 1250 e ⁺ : 800
Circumference or length (km)	0.024	0.366	0.2404	0.23753	0.098
Interaction regions	2	1	2	1	1
Magnetic length of dipole (m)	1.1	2	1.6	outer ring: 1.6 inner ring: 1.41	outer ring: 1.2 inner ring: 1
Length of standard cell (m)	12	7.2	6.6	outer ring: 6.6 inner ring: 6.2	n/a
Phase advance per cell (deg)	H:745 V:385	65	≈ 60	60–90 non-standard cells	—
Dipoles in ring	8	78	40 + 4 weak	84 + 8 weak	8
Quadrupoles in ring	24 + 4 s.c.	150	68	134+2 s.c.	48
Peak magnetic field (T)	2.4	0.6	0.903 at 2.8 GeV	outer ring: 0.677 inner ring: 0.766	1.2

*KLOE-2

†SIDDHARTINO

‡SIDDHARTA-2

High-Energy Collider Parameters: e^+e^- Colliders (II)

Table 32.2: Updated in March 2020 with numbers received from representatives of the colliders (contact E. Pianori, LBNL). The table shows the parameter values achieved. Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy; H and V indicate horizontal and vertical directions; s.c. stands for superconducting. ILC and CLIC parameters are documented in the Accelerator physics of colliders review.

	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	SLC (SLAC)
Physics start date	1979	2002	1989	1989
Physics end date	2002	2008	2000	1998
Maximum beam energy (GeV)	6	6	100 - 104.6	50
Delivered integrated luminosity per experiment (fb^{-1})	41.5	2.0	0.221 at Z peak 0.501 at 65 – 100 GeV 0.275 at >100 GeV	0.022
Luminosity ($10^{30} \text{ cm}^{-2}\text{s}^{-1}$)	1280 at 5.3 GeV	76 at 2.08 GeV	24 at Z peak 100 at > 90 GeV	2.5
Time between collisions (μs)	0.014 to 0.22	0.014 to 0.22	22	8300
Full crossing angle (μ rad)	± 2000	± 3300	0	0
Energy spread (units 10^{-3})	0.6 at 5.3 GeV	0.82 at 2.08 GeV	0.7→1.5	1.2
Bunch length (cm)	1.8	1.2	1.0	0.1
Beam radius (μm)	H:460 V:4	H:340 V:6.5	H:200→300 V:2.5→8	H:1.5 V:0.5
Free space at interaction point (m)	± 2.2 (± 0.6 to REC quads)	± 2.2 (± 0.3 to PM quads)	± 3.5	± 2.8
Luminosity lifetime (hr)	2–3	2–3	20 at Z peak 10 at > 90 GeV	—
Turn-around time (min)	5 (topping up)	1.5 (topping up)	50	120 Hz (pulsed)
Injection energy (GeV)	1.8–6	1.5–6	22	45.64
Transverse emittance (10^{-9} m)	210 1	120 3.5	H:20–45 V:0.25→1	H:0.5 V:0.05
β^* , amplitude function at interaction point (m)	1.0 0.018	0.94 0.012	1.5 0.05	0.0025 0.0015
Beam-beam tune shift per crossing (10^{-4}) or disruption	250 620	e^- : 420 (H), 280 (V) e^+ : 410 (H), 270 (V)	830	0.75 (H) 2.0 (V)
RF frequency (MHz)	500	500	352.2	2856
Particles per bunch (units 10^{10})	1.15	4.7	45 in collision 60 in single beam	4.0
Bunches per ring per species	9 trains of 5 bunches	8 trains of 3 bunches	4 trains of 1 or 2	1
Average beam current per species (mA)	340	72	4 at Z peak 4→6 at > 90 GeV	0.0008
Beam polarization (%)	—	—	55 at 45 GeV 5 at 61 GeV	e^- : 80
Circumference or length (km)	0.768	0.768	26.66	1.45 +1.47
Interaction regions	1	1	4	1
Magnetic length of dipole (m)	1.6–6.6	1.6–6.6	11.66/pair	2.5
Length of standard cell (m)	16	16	79	5.2
Phase advance per cell (deg)	45–90 (no standard cell)	45–90 (no standard cell)	102/90	108
Dipoles in ring	86	84	3280 + 24 inj. + 64 weak	460+440
Quadrupoles in ring	101 + 4 s.c.	101 + 4 s.c.	520 + 288 + 8 s.c.	—
Peak magnetic field (T)	0.3 / 0.8 at 8 GeV	0.3 / 0.8 at 8 GeV, 2.1 wigglers at 1.9 GeV	0.135	0.597

High-Energy Collider Parameters: ep , e^+e^- Colliders (III)

Table 32.3: Updated in March 2022 with numbers received from representatives of the colliders (contact E. Pianori, LBNL). The table shows the parameter values achieved. Design parameters for SuperKEKB may be found in our 2018 edition (Phys. Rev. **D98**, 030001 (2018)) Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy; H and V indicate horizontal and vertical directions; s.c. stands for superconducting.

	HERA (DESY)	KEKB (KEK)	PEP-II (SLAC)	SuperKEKB (KEK)
Physics start date	1992	1999	1999	2018
Physics end date	2007	2010	2008	—
Particles collided	ep	e^+e^-	e^+e^-	e^+e^-
Maximum beam energy (TeV)	e : 0.030 p : 0.92	e^- : 8.33 (8.0 nominal) e^+ : 3.64 (3.5 nominal)	e^- : 7–12 (9.0 nominal) e^+ : 2.5–4 (3.1 nominal)	e^- : 7 e^+ : 4
Delivered integrated luminosity per exp. (fb^{-1})	0.8	1040	557	491
Luminosity ($10^{30} \text{ cm}^{-2}\text{s}^{-1}$)	75	21083	12069 (design: 3000)	4.71×10^4
Time between collisions (ns)	96	5.9 or 7.86	4.2	4.2
Full crossing angle (μ rad)	0	$\pm 11000^*$	0	± 41500
Energy spread (units 10^{-3})	e : 0.91 p : 0.2	e^-/e^+ : 0.67/0.73	e^-/e^+ : 0.61/0.77	e^-/e^+ : 0.64/0.81
Bunch length (cm)	e : 0.83 p : 8.5	0.65	e^-/e^+ : 1.1/1.0	e^-/e^+ : 0.6/0.6
Beam radius (μm)	e : 110 (H), 30 (V) p : 111 (H), 30 (V)	H: 124 (e^-), 117 (e^+) V: 1.9	157 4.7	e^- : 16.6 (H), 0.22 (V) e^+ : 17.9 (H), 0.22 (V)
Free space at interaction point (m)	± 2	+0.75/−0.58 (+300/−500) mrad cone	± 0.2 , ± 300 mrad cone	e^- : +1.20/−1.28 e^+ : +0.78/−0.73 (+300/−500) mrad cone
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	10	continuous	continuous	continuous
Turn-around time (min)	e : 75, p : 135	continuous	continuous	continuous
Injection energy (GeV)	e : 12 p : 40	e^-/e^+ : 8.0/3.5 (nominal)	e^-/e^+ : 9.0/3.1 (nominal)	e^-/e^+ : 7/4
Transverse emittance (10^{-9} m)	e : 20 (H), 3.5 (V) p : 5 (H), 5 (V)	e^- : 24 (57 †) (H), 0.61 (V) e^+ : 18 (55 †) (H), 0.56 (V)	e^- : 48 (H), 1.8 (V) e^+ : 24 (H), 1.8 (V)	e^- : 4.6 (H), 0.05 (V) e^+ : 4.0 (H), 0.05 (V)
β^* , amplitude function at interaction point (m)	e : 0.6 (H), 0.26 (V) p : 2.45 (H), 0.18 (V)	e^- : 1.2 (0.27 †) (H), 0.0059 (V) e^+ : 1.2 (0.23 †) (H), 0.0059 (V)	e^- : 0.50 (H), 0.012 (V) e^+ : 0.50 (H), 0.012 (V)	e^- : 0.060 (H), 1×10^{-3} (V) e^+ : 0.080 (H), 1×10^{-3} (V)
Beam-beam tune shift per crossing (units 10^{-4})	e : 190 (H), 450 (V) p : 12 (H), 9 (V)	e^- : 1020 (H), 900 (V) e^+ : 1270 (H), 1290 (V)	e^- : 703 (H), 498 (V) e^+ : 510 (H), 727 (V)	e^- : 15 (H), 278 (V) e^+ : 27 (H), 398 (V)
RF frequency (MHz)	e : 499.7 p : 208.2/52.05	508.887	476	508.887
Particles per bunch (units 10^{10})	e : 3 p : 7	e^-/e^+ : 4.7/6.4	e^-/e^+ : 5.2/8.0	e^-/e^+ : 3.12/3.81
Bunches per ring per species	e : 189 p : 180	1585	1732	2249
Average beam current per species (mA)	e : 40 p : 90	e^-/e^+ : 1188/1637	e^-/e^+ : 1960/3026	e^-/e^+ : 1118/1393
Beam polarization (%)	—	—	—	—
Circumference or length (km)	6.336	3.016	2.2	3.016
Interaction regions	2 colliding beams 1 fixed target (e beam)	1	1	1
Magnetic length of dipole (m)	e : 9.185; p : 8.82	e^-/e^+ : 5.86/0.915	e^-/e^+ : 5.4/0.45	e^-/e^+ : 5.9/4.0
Length of standard cell (m)	e : 23.5 p : 47	e^-/e^+ : 75.7/76.1	15.2	e^-/e^+ : 75.7/76.1
Phase advance per cell (deg)	e : 60 p : 90	450	e^-/e^+ : 60/90	450
Dipoles in ring	e : 396 p : 416	e^-/e^+ : 116/112	e^-/e^+ : 192/192	e^-/e^+ : 116/112
Quadrupoles in ring	e : 580 p : 280	e^-/e^+ : 452/452	e^-/e^+ : 290/326	e^-/e^+ : 466/460
Peak magnetic field (T)	e : 0.274; p : 5	e^-/e^+ : 0.25/0.72	e^-/e^+ : 0.18/0.75	e^-/e^+ : 0.22/0.19

* KEKB was operated with crab crossing from 2007 to 2010.

† With dynamic beam-beam effect.

High-Energy Collider Parameters: $\bar{p}p$, pp Colliders

Table 32.4: Updated in March 2024 with numbers received from representatives of the colliders (contact E. Pianori, LBNL). The table shows the parameter values achieved. Parameters for the defunct $Spp\bar{p}S$ collider may be found in our 2002 edition (Phys. Rev. D66, 010001 (2002)). Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy; H and V indicate horizontal and vertical directions; s.c. stands for superconducting.

	TEVATRON*	RHIC	LHC			
	(Fermilab)	Brookhaven	(CERN)			
Physics start date	1987	2001	2009 (Run 1)	2015 (Run 2)	2022 (Run 3)	2029 (HL-LHC)
Physics end date	2011	—	—			
Particles collided	$p\bar{p}$	pp (polarized)	pp			
Maximum beam energy (TeV)	0.980	0.255 55% polarization	4.0	6.5	6.8	7.0
Max. delivered integrated luminosity per exp. (fb^{-1})	12	0.38 at 100 GeV 1.3 at 250/255 GeV	23.3 at 4.0 TeV 6.1 at 3.5 TeV	160	70	250/y
Luminosity ($10^{30} \text{ cm}^{-2}\text{s}^{-1}$)	431	245 (pk) 160 (avg)	7.7×10^3	2.1×10^4	2×10^4 (leveled)	5.0×10^4 (leveled)
Time between collisions (ns)	396	107	49.90	24.95	24.95	24.95
Full crossing angle (μ rad)	0	0	290	$320 \rightarrow 260^\dagger$	$320 \rightarrow 270^\dagger$	500
Energy spread (units 10^{-3})	0.14	0.15	0.1445	0.11	0.11	0.11
Bunch length (cm)	p : 50 \bar{p} : 45	60	9.4	8	9.7	7.6
Beam radius (10^{-6} m)	p : 28 \bar{p} : 16	85	18.8	8.5^\ddagger	9.3^\ddagger	7^\ddagger
Free space at interaction point (m)	± 6.5	16	38	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	6 (avg)	7.5	≈ 6	8.4	12^\S	≈ 7.5 (leveled)
Turn-around time (min)	90	25	180	150	180^\P	150
Injection energy (TeV)	0.15	0.023	0.450	0.450	0.450	0.450
Transverse emittance (10^{-9} m)	p : 3 \bar{p} : 1	11	0.59	0.29	0.29	0.33
β^* , ampl. function at interaction point (m)	0.28	0.65	0.6	$0.3 \rightarrow 0.25^\parallel$	$1.2 \rightarrow 0.3^\parallel$	$1 \rightarrow 0.15^\parallel$
Beam-beam tune shift per crossing (units 10^{-4})	p : 120 \bar{p} : 120	73	72	45	57^\S	104
RF frequency (MHz)	53	accel: 9 store: 28	400.8	400.8	400.8	400.8
Particles per bunch (units 10^{10})	p : 26 \bar{p} : 9	18.5	16	11	16	22
Bunches per ring per species	36	111	1380	2556 2544 (i.r. 1/5**)	2464 2452 (i.r. 1/5**)	2760 2748 (i.r. 1/5**)
Average beam current per species (mA)	p : 70 \bar{p} : 24	257	400	510	710	1094
Circumference (km)	6.28	3.834	26.659			
Interaction regions	2 high \mathcal{L}	6 total, 2 high \mathcal{L}	4 total, 2 high \mathcal{L}			
Magnetic length of dipole (m)	6.12	9.45	14.3			
Length of standard cell (m)	59.5	29.7	106.90			
Phase advance per cell (deg)	67.8	84	90			
Dipoles in ring	774	192 per ring + 12 common	1232 main dipoles			
Quadrupoles in ring	216	246 per ring	482 2-in-1 24 1-in-1			
Magnet types	s.c., $\cos\theta$ warm iron	s.c., $\cos\theta$ cold iron	s.c., 2-in-1 cold iron			
Peak magnetic field (T)	4.4	3.5	$8.3^{\ddagger\dagger}$			

* Other TEVATRON parameters: \bar{p} source accum. rate: $25 \times 10^{10} \text{ hr}^{-1}$; max. no. of \bar{p} stored: 3.4×10^{12} (Accumulator), 6.1×10^{12} (Recycler).

† Variable crossing angle decreasing during the fill with the reduction in bunch population

‡ Minimum beam radius during levelling

§ Value at start of levelling

¶ Most likely value as observed in 2023

$^\parallel$ β^* levelling

** Number of bunches colliding at the interaction regions (i.r.) 1 (ATLAS) and 5 (CMS).

‡† Value for design beam energy of 7 TeV.

High-Energy Collider Parameters: Heavy Ion Colliders

Table 32.5: Updated in March 2024 with numbers received from representatives of the collider (contact E. Pianori, LBNL) The table shows the parameter values achieved. For the LHC, only maximum values for the ATLAS and CMS experiments are provided (ALICE and LHCb have different requirements for energy and luminosity). Design values for a high-luminosity upgrade are also given. Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy; s.c. stands for superconducting. pk and avg denote peak and average values.

	RHIC (Brookhaven)				LHC (CERN)			
	2000	2012 / 2018 / 2018 / 2012 / 2004 2021 / 2014 / 2002 / 2015 / 2015			2010	2012	2017	≥ 2029 (high lum.)*
Physics start date	2000				2010	2012	2017	≥ 2029 (high lum.)*
Physics end date		—				—		
Particles collided	Au Au	U U / Zr Zr / Ru Ru / Cu Au / Cu Cu O O / h Au / d Au / p Au / p Al			Pb Pb	p Pb	Xe Xe	Pb Pb
Max. beam energy (TeV/n)	0.1	0.1			2.68	p:6.5 Pb:2.56	2.72	2.76
$\sqrt{s_{NN}}$ (TeV)	0.2	0.2			5.36	8.16	5.44	5.5
Max. delivered int. nucleon-pair lumin. per exp. (pb ⁻¹)	2639 (at 100 GeV/n)	21 / 36 / 36.9 / 167 / 60 8.2 / 43 / 169 / 124 / 63 (all at 100 GeV/n)			84.8	194	0.05	$\approx 121/y$
Luminosity (10 ²⁷ cm ⁻² s ⁻¹)	pk: 15.5 avg: 8.7	pk: 0.4 / 4.8 / 3.8 / 12 / 21 450 / 170 / 850 / 880 / 7600 avg: 0.6 / 2.2 / 2.1 / 10 / 8 230 / 100 / 500 / 450 / 3800			6.4 [†]	900	0.4	6.4 (leveled)
Time between collisions (ns)	107	107 / 107 / 107 / 107 / 321 107 / 107 / 107 / 107 / 107			49.9	99.8 / 149.7	≈ 5500	49.9
Full crossing angle (μ rad)	0	0			200	280	300	340
Energy spread (units 10 ⁻³)	0.75	0.75			0.13	0.11	0.11	0.11
Bunch length (cm)	30	30			9.1	p / Pb: 9 / 11.5	11	7.9
Beam radius (10 ⁻⁶ m)	114 [‡]	123 [‡] / 87 [‡] / 88 [‡] / 163 [‡] / 145 [‡] 100 [‡] / 136 [‡] / 124 [‡] / 147 [‡] / 128 [‡]			20	19	12	17
Free space at inter. point (m)	16	16			38	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	1	-0.35 [§] / ∞ [¶] / ∞ [¶] / ∞ [§] / 1.8 ∞ / 0.6 / ∞ [§] / 0.5 / 0.25			2.8	≈ 2	≈ 6	∞
Turn-around time (min)	30	60 ^{**} / 40 ^{**} / 40 ^{**} / 160 ^{**} / 90 ^{**} 45 ^{**} / 45 ^{**} / 90 ^{**} / 60 ^{**} / 50 ^{**}			144	150	180	≈ 200
Injection energy (TeV/n)	0.011	0.011			0.177	p / Pb: 0.45 / 0.177	0.188	0.177
Transverse emittance (10 ⁻⁹ m)	19 [‡]	22 [‡] / 10.7 [‡] / 11.2 [‡] / 38 [‡] / 23 [‡] 12 [‡] / 19 [‡] / 22 [‡] / 26 [‡] / 21 [‡]			0.80	0.29	0.3	0.5
β^* , ampl. function at interaction point (m)	0.7	0.7 / 0.7 / 0.7 / 0.7 / 0.9 0.7 / 1.0 / 0.7 / 0.8 / 0.8			0.5	0.5	0.4	0.5
Beam-beam tune shift per crossing (units 10 ⁻⁴)	39 [‡]	6 [‡] / 18 [‡] / 21 [‡] / 14 [‡] , 14 [‡] / 30 [‡] / 34 [‡] 42 [‡] , 22 [‡] / 40 [‡] , 27 [‡] / 53 [‡] , 41 [‡] / 80 [‡] , 59 [‡]			3.1	15	≈ 10	4.3
RF frequency (MHz)		accel: 28, store: 197			400.8	400.8	400.8	400.8
Particles per bunch (units 10 ¹⁰)	0.20	0.03 / 0.1 / 0.1 / 0.4, 0.13 / 0.45 / 0.85 4.5, 0.13 / 13, 0.20 / 22.5, 0.16 / 24, 1.1			0.018 (r.m.s.)	p:2.6 Pb:0.022	0.027	0.018
Bunches per ring per species	111	111 / 111 / 111 / 111 / 37 106 / 111 / 111 / 111 / 111			960 ^{††}	p:540 Pb:684	16	1240
Average beam current per species (mA)	224	38 / 56 / 61 / 160,138 / 60 / 95 125,143 / 181,213 / 313,176 / 334,199			25.5	p:16 Pb:15	0.54	33
Circumference (km)		3.834				26.659		
Interaction regions		6 total, 2 high \mathcal{L}				4 total, 3 high \mathcal{L}		
Magnetic length of dipole (m)		9.45				14.3		
Length of standard cell (m)		29.7				106.90		
Phase advance per cell (deg)	93	84 / 84 / 84 / 84 / 84 / 84 93 / 84(d), 93 / 84(p), 93 / 84(p), 93				90		
Dipoles in ring		192 per ring, + 12 common				1232, main dipoles		
Quadrupoles in ring		246 per ring				482 2-in-1, 24 1-in-1		
Magnet Type		s.c. cos θ , cold iron				s.c., 2 in 1, cold iron		
Peak magnetic field (T)		3.5				8.3		

*For HL-LHC. Conservative estimates.

[†]Highest value achieved in ALICE.

[‡]Initial value, increases (decreases) without (with) cooling.

[§]Negative or infinite decay time is effect of cooling.

[¶]luminosity leveled to flat after set to target value, with cooling.

^{||} for a typical good fill without luminosity levelling.

** measured minimum, not theoretical.

^{††} 1240 bunches per ring were also used, but with lower peak performance due to lower bunch intensity.