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

Updated in January 2016 with numbers received from representatives of the colliders (contact S. Pagan Griso, 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 (2.3 max)	0.510
Delivered integrated luminosity per exp. (fb^{-1})	0.030	0.027	0.11	10.3	$\approx$ 4.7 in 2001-2007 $\approx$ 2.7 w/crab-waist $\approx$ 1.8 since Nov 2014
Luminosity (10^{30} $cm^{-2}s^{-1}$)	100	20	12.6 at 1.843 GeV 5 at 1.55 GeV	853	453
Time between collisions (μs)	0.04	0.6	0.8	0.008	0.0027
Full crossing angle (μ rad)	0	0	0	2.2×10^4	5×10^4
Energy spread (units 10^{-3})	0.64	1	0.58 at 2.2 GeV	0.52	0.40
Bunch length (cm)	4	5	$\approx$ 5	$\approx$ 1.5	low current: 1 at 15mA: 2
Beam radius (10^{-6} m)	125 (round)	H: 1000 V: 30	H: 890 V: 37	H: 358 V: 4.8	H: 260 V: 4.8
Free space at interaction point (m)	$\pm$1	$\pm$2	$\pm$2.15	$\pm$0.63	$\pm$0.295
Luminosity lifetime (hr)	continuous	2	7–12	1.5	0.2
Turn-around time (min)	continuous	18	32	15	2 (topping up)
Injection energy (GeV)	0.2–1.0	1.8	1.55	1.89	on energy
Transverse emittance (10^{-9} m)	H: 250 V: 250	H: 200 V: 20	H: 660 V: 28	H: 128 V: 1.73	H: 260 V: 2.6
β^*, amplitude function at interaction point (m)	H: 0.06 – 0.11 V: 0.06 – 0.10	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: 750 V: 750	500	350	390	440 (crab-waist test)
RF frequency (MHz)	172	180	199.53	499.8	356
Particles per bunch (units 10^{10})	16	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	92	100 to 105 (120 buckets)
Average beam current per species (mA)	150	80	40 at 2 GeV 22 at 1.55 GeV	701	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)	1.2	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: 738 V: 378	65	$\approx$ 60	60–90 non-standard cells	—
Dipoles in ring	8	78	40 + 4 weak	84 + 8 weak	8
Quadrupoles in ring	20	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

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

Updated in January 2016 with numbers received from representatives of the colliders (contact S. Pagan Griso, LBNL). The table shows the parameter values achieved. For future colliders, design values are quoted. 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.

	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	SLC (SLAC)	ILC (TBD)	CLIC (TBD)
Physics start date	1979	2002	1989	1989	TBD	TBD
Physics end date	2002	2008	2000	1998	—	—
Maximum beam energy (GeV)	6	6	100 - 104.6	50	250 (upgradeable to 500)	1500 (first phase: 190)
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} $cm^{-2}s^{-1}$)	1280 at 5.3 GeV	76 at 2.08 GeV	24 at Z peak 100 at > 90 GeV	2.5	$1.5\times10^{4\ddagger}$	6×10^4
Time between collisions (μs)	0.014 to 0.22	0.014 to 0.22	22	8300	$0.55^\dagger$	$0.0005^\dagger$
Full crossing angle (μ rad)	±2000	±3300	0	0	14000	20000
Energy spread (units 10^{-3})	0.6 at 5.3 GeV	0.82 at 2.08 GeV	0.7→1.5	1.2	1	3.4
Bunch length (cm)	1.8	1.2	1.0	0.1	0.03	0.0044
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	H: 0.474 V: 0.0059	H: 0.045 * V: 0.0009
Free space at interaction point (m)	±2.2 (±0.6 to REC quads)	±2.2 (±0.3 to PM quads)	±3.5	±2.8	±3.5	±3.5
Luminosity lifetime (hr)	2–3	2–3	20 at Z peak 10 at > 90 GeV	—	n/a	n/a
Turn-around time (min)	5 (topping up)	1.5 (topping up)	50	120 Hz (pulsed)	n/a	n/a
Injection energy (GeV)	1.8–6	1.5–6	22	45.64	n/a	n/a
Transverse emittance (10^{-9} m)	H: 210 V: 1	H: 120 V: 3.5	H: 20–45 V: 0.25 → 1	H: 0.5 V: 0.05	H: 0.02 V: 7×10^{-5}	H: 2.2×10^{-4} V: 6.8×10^{-6}
β^*, amplitude function at interaction point (m)	H: 1.0 V: 0.018	H: 0.94 V: 0.012	H: 1.5 V: 0.05	H: 0.0025 V: 0.0015	H: 0.01 V: 5×10^{-4}	H: 0.0069 V: 6.8×10^{-5}
Beam-beam tune shift per crossing (10^{-4}) or disruption	H: 250 V: 620	e^-: 420 (H), 280 (V) e^+: 410 (H), 270 (V)	830	0.75 (H) 2.0 (V)	n/a	7.7
RF frequency (MHz)	500	500	352.2	2856	1300	11994
Particles per bunch (units 10^{10})	1.15	4.7	45 in collision 60 in single beam	4.0	2	0.37
Bunches per ring per species	9 trains of 5 bunches	8 trains of 3 bunches	4 trains of 1 or 2	1	1312	312 (in train)
Average beam current per species (mA)	340	72	4 at Z peak 4→6 at > 90 GeV	0.0008	6 (in pulse)	1205 (in train)
Beam polarization (%)	—	—	55 at 45 GeV 5 at 61 GeV	e^-: 80	e^-: > 80% e^+: < 60%	e^-: 70% at IP
Circumference or length (km)	0.768	0.768	26.66	1.45 +1.47	31	50
Interaction regions	1	1	4	1	1	1
Magnetic length of dipole (m)	1.6–6.6	1.6–6.6	11.66/pair	2.5	n/a	n/a
Length of standard cell (m)	16	16	79	5.2	n/a	n/a
Phase advance per cell (deg)	45–90 (no standard cell)	45–90 (no standard cell)	102/90	108	n/a	n/a
Dipoles in ring	86	84	3280 + 24 inj. + 64 weak	460+440	n/a	n/a
Quadrupoles in ring	101 + 4 s.c.	101 + 4 s.c.	520 + 288 + 8 s.c.	—	n/a	n/a
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	n/a	n/a

†Time between bunch trains: 200ms (ILC) and 20ms (CLIC).

‡Geometrical luminosity. The actual value may vary by $\approx 20\%$ depending on assumptions.

*Effective beam size including non-linear and chromatic effects.

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

Updated in January 2016 with numbers received from representatives of the colliders (contact S. Pagan Griso, LBNL). The table shows the parameter values achieved. For future colliders, design values are quoted. 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.

	KEKB (KEK)	PEP-II (SLAC)	SuperKEKB (KEK)
Physics start date	1999	1999	2017
Physics end date	2010	2008	—
Maximum beam energy (GeV)	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})	1040	557	—
Luminosity (10^{30} $cm^{-2}s^{-1}$)	21083	12069 (design: 3000)	8×10^5
Time between collisions (μs)	0.00590 or 0.00786	0.0042	0.004
Full crossing angle (μ rad)	$\pm 11000^\dagger$	0	± 41500
Energy spread (units 10^{-3})	0.7	e^-/e^+: 0.61/0.77	e^-/e^+: 0.64/0.81
Bunch length (cm)	0.65	e^-/e^+: 1.1/1.0	e^-/e^+: 0.5/0.6
Beam radius (μm)	H: 124 (e^-), 117 (e^+) V: 1.9	H: 157 V: 4.7	e^-: 11 (H), 0.062 (V) e^+: 10 (H), 0.048 (V)
Free space at interaction point (m)	+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
Luminosity lifetime (hr)	continuous	continuous	continuous
Turn-around time (min)	continuous	continuous	continuous
Injection energy (GeV)	e^-/e^+ : 8.0/3.5 (nominal)	e^-/e^+ : 9.0/3.1 (nominal)	e^-/e^+ : 7/4
Transverse emittance (10^{-9} m)	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), 0.013 (V) e^+: 3.2 (H), 0.0086 (V)
β^*, amplitude function at interaction point (m)	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^-: 0.025 (H), 3×10^{-4} (V) e^+: 0.032 (H), 2.7×10^{-4} (V)
Beam-beam tune shift per crossing (units 10^{-4})	e^-: 1020 (H), 900 (V) e^+: 1270 (H), 1290 (V)	e^-: 703 (H), 498 (V) e^+: 510 (H), 727 (V)	e^-: 12 (H), 807 (V) e^+: 28 (H), 881 (V)
RF frequency (MHz)	508.887	476	508.887
Particles per bunch (units 10^{10})	e^-/e^+: 4.7/6.4	e^-/e^+: 5.2/8.0	e^-/e^+: 6.53/9.04
Bunches per ring per species	1585	1732	2500
Average beam current per species (mA)	e^-/e^+: 1188/1637	e^-/e^+: 1960/3026	e^-/e^+: 2600/3600
Beam polarization (%)	—	—	—
Circumference or length (km)	3.016	2.2	3.016
Interaction regions	1	1	1
Magnetic length of dipole (m)	e^-/e^+ : 5.86/0.915	e^-/e^+: 5.4/0.45	e^-/e^+ : 5.9/4.0
Length of standard cell (m)	e^-/e^+ : 75.7/76.1	15.2	e^-/e^+ : 75.7/76.1
Phase advance per cell (deg)	450	e^-/e^+: 60/90	450
Dipoles in ring	e^-/e^+ : 116/112	e^-/e^+: 192/192	e^-/e^+ : 116/112
Quadrupoles in ring	e^-/e^+ : 452/452	e^-/e^+: 290/326	e^-/e^+ : 466/460
Peak magnetic field (T)	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: ep, $\overline{\text{p}}$p, pp Colliders

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	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)	LHC (CERN)		
Physics start date	1992	1987	2001	2009	2015	2024 (HL-LHC)
Physics end date	2007	2011	—	—		
Particles collided	ep	$p\overline{p}$	pp (polarized)	pp		
Maximum beam energy (TeV)	e: 0.030 p: 0.92	0.980	0.255 53% polarization	4.0	6.5	7.0
Maximum delivered integrated luminosity per exp. (fb^{-1})	0.8	12	0.38 at 100 GeV 0.75 at 250/255 GeV	23.3 at 4.0 TeV 6.1 at 3.5 TeV	4.2	250/y
Luminosity (10^{30} $\text{cm}^{-2}\text{s}^{-1}$)	75	431	245 (pk) 160 (avg)	7.7×10^3	5×10^3	5.0×10^4 (leveled)
Time between collisions (ns)	96	396	107	49.90	24.95	24.95
Full crossing angle (μ rad)	0	0	0	290	290	590
Energy spread (units 10^{-3})	e: 0.91 p: 0.2	0.14	0.15	0.1445	0.105	0.123
Bunch length (cm)	e: 0.83 p: 8.5	p: 50 $\bar{\text{p}}$: 45	60	9.4	9	9
Beam radius (10^{-6} m)	e: $110(H), 30(V)$ p: $111(H), 30(V)$	p: 28 $\bar{\text{p}}$: 16	85	18.8	21	7
Free space at interaction point (m)	± 2	± 6.5	16	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	10	6 (avg)	7.5	≈ 6	≈ 30	≈ 6 (leveled)
Turn-around time (min)	e: 75, p: 135	90	25	180	134	180
Injection energy (TeV)	e: 0.012 p: 0.040	0.15	0.023	0.450	0.450	0.450
Transverse emittance (10^{-9} m)	e: $20(H), 3.5(V)$ p: $5(H), 5(V)$	p: 3 $\bar{\text{p}}$: 1	13	0.59	0.5	0.34
β^*, ampl. function at interaction point (m)	e: $0.6(H), 0.26(V)$ p: $2.45(H), 0.18(V)$	0.28	0.65	0.6	0.8	0.15
Beam-beam tune shift per crossing (units 10^{-4})	e: $190(H), 450(V)$ p: $12(H), 9(V)$	p: 120 $\bar{\text{p}}$: 120	73	72	37	110
RF frequency (MHz)	e: 499.7 p: 208.2/52.05	53	accel: 9 store: 28	400.8	400.8	400.8
Particles per bunch (units 10^{10})	e: 3 p: 7	p: 26 $\bar{\text{p}}$: 9	18.5	16	12	22
Bunches per ring per species	e: 189 p: 180	36	111	1380	2244 2232 (i.r. 1/5†)	2748 2736 (i.r. 1/5†)
Average beam current per species (mA)	e: 40 p: 90	p: 70 $\bar{\text{p}}$: 24	257	400	467	1200
Circumference (km)	6.336	6.28	3.834	26.659		
Interaction regions	2 colliding beams 1 fixed target (e beam)	2 high $\mathscr{L}$	6 total, 2 high $\mathscr{L}$	4 total, 2 high $\mathscr{L}$		
Magnetic length of dipole (m)	e: 9.185 p: 8.82	6.12	9.45	14.3		
Length of standard cell (m)	e: 23.5 p: 47	59.5	29.7	106.90		
Phase advance per cell (deg)	e: 60 p: 90	67.8	84	90		
Dipoles in ring	e: 396 p: 416	774	192 per ring + 12 common	1232 main dipoles		
Quadrupoles in ring	e: 580 p: 280	216	246 per ring	482 2-in-1 24 1-in-1		
Magnet types	e: C-shaped p: s.c., collared, warm iron	s.c., $\cos\theta$ warm iron	s.c., $\cos\theta$ cold iron	s.c., 2 in 1 cold iron		
Peak magnetic field (T)	e: 0.274, p: 5	4.4	3.5	8.3‡		

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

†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

Updated in January 2016 with numbers received from representatives of the colliders (contact S. Pagan Griso, LBNL). The table shows the parameter values achieved. For LHC, the parameters expected at the ATLAS experiment for running in 2016 and the 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)			
Physics start date	2000	2012 / 2012 / 2004 / 2014 2002 / 2015 / 2015	2010	2012	2016 (expected)	$\geq$ 2021 (high lum.)‡
Physics end date	—		—			
Particles collided	Au Au	U U / Cu Au / Cu Cu / h Au d Au / p Au / p Al	Pb Pb	p Pb	p Pb	Pb Pb
Maximum beam energy (TeV/n)	0.1	0.1	2.51	p: 4 Pb: 1.58	p: 6.5 Pb: 2.56	2.76
$\sqrt{s_{NN}}$ (TeV)	0.2	0.2	5.02	5.0	8.16	5.5
Max. delivered int. nucleon-pair lumin. per exp. (pb^{-1})	1484 (at 100 GeV/n)	21 / 167 / 65 / 43 103 / 125 / 64 (all at 100 GeV/n)	30.3	6.6	$\approx 10/y$	$\approx 75 - 90/y$
Luminosity (10^{27} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	pk: 8.4 avg: 8.0	pk: 0.9 / 12 / 20 / 170 270 / 880 / 7150 avg: 0.6 / 10 / 0.8 / 100 140 / 450 / 4000	3.6	100 (leveled) 116 (ATLAS/CMS)	≈ 500	6 (leveled)
Time between collisions (ns)	107	107 / 107 / 321 / 107 107 / 107 / 107	99.8 / 149.7	199.6 / 224.6	99.8 / 149.7	49.9
Full crossing angle (μ rad)	0	0	290	120	290	> 200
Energy spread (units 10^{-3})	0.75	0.75	0.11	0.11	0.11	0.11
Bunch length (cm)	30	30	8.0	p / Pb: 9 / 11.5	p / Pb: 9 / 11.5	7.9
Beam radius (10^{-6} m)	55	50 / 160 / 145 / 135 145 / 145 / 145	55	p: 19 Pb: 27	17	16
Free space at interaction point (m)	16	16	38	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	1	-0.35†/ ∞†/ 1.8 / 0.6 1.5 / 0.5 / 0.25	2.6	≈ 6	≈ 2	≈ 2
Turn-around time (min)	30	60 / 160 / 90 / 45 90 / 60 / 50	≈ 180	≈ 240	≈ 180	≈ 180
Injection energy (TeV/n)	0.011	0.011	0.177	p / Pb: 0.45 / 0.177	p / Pb: 0.45 / 0.177	0.177
Transverse emittance (10^{-9} m)	6	4 / 11 / 23 / 18 25 / 25 / 23	1.5	p: 0.5 Pb: 0.9	0.29	0.5
β^*, ampl. function at interaction point (m)	0.5	0.7 / 0.7 / 0.9 / 1.0 0.85 / 0.8 / 0.8	0.8	0.8	0.5	0.5
Beam-beam tune shift per crossing (units 10^{-4})	25	7 / 14 (Cu), 14 (Au) / 30 42 (h), 22 (Au) / 21 (d), 17 (Au) 53 (p), 41 (Au) / 73 (p) 57 (Au)	9	p: 9 Pb: 10	10	10
RF frequency (MHz)	accel: 28 store: 197	accel: 28 store: 197	400.8	400.8	400.8	400.8
Particles per bunch (units 10^{10})	0.16	0.03 / 0.4 (Cu), 0.13 (Au) / 0.45 4.5 (h), 0.13 (Au) / 10 (d), 0.1 (Au) 22.5 (p), 0.16 (Au) / 24 (p), 1.1 (Al)	0.019 (r.m.s.)	p: 1.6 Pb: 0.014	p: 1.8 Pb: 0.019	0.017
Bunches per ring per species	111	111 / 111 / 37 / 111 95 / 111 / 111	518	338	518	≈ 1100
Average beam current per species (mA)	176	38 / 159 (Cu), 138 (Au) / 60 125 (h), 143 (Au) / 119 (d), 94 (Au) 312 (p), 176 (Au) / 333 (p), 199 (Al)	14.9	p: 9.7 Pb: 7	p: 17 Pb: 15	28
Circumference (km)	3.834		26.659			
Interaction regions	6 total, 2 high $\mathscr{L}$		3 high $\mathscr{L}$ + 1			
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 / 93 84 (d), 93 (Au) / 84 (p), 93 (Au) 84 (p), 93 (Al)	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. $\cos\theta$, cold iron		s.c., 2 in 1, cold iron			
Peak magnetic field (T)	3.5		8.3			

†Negative or infinite decay time is effect of cooling.

‡High luminosity upgrade expected >= 2021; will extend throughout HL-LHC running. Very preliminary, conservative estimates.