

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

Updated in March 2018 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 (2.3 max)	0.510
Delivered integrated luminosity per exp. (fb^{-1})	0.125	0.027	0.11	17.5	≈ 4.7 in 2001-2007 ≈ 2.7 w/crab-waist ≈ 1.8 since Nov 2014
Luminosity ($10^{30} \text{ cm}^{-2}\text{s}^{-1}$)	40	20	12.6 at 1.843 GeV 5 at 1.55 GeV	1000	453
Time between collisions (μs)	0.04	0.6	0.8	0.008	0.0027
Full crossing angle ($\mu \text{ rad}$)	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	≈ 1.2	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	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 : 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 : 0.0129	H : 0.26 V : 0.009
Beam-beam tune shift per crossing (units 10^{-4})	H : 850 V : 850	500	350	383	440 (crab-waist test)
RF frequency (MHz)	172	180	199.53	499.8	356
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 105 (120 buckets)
Average beam current per species (mA)	160	80	40 at 2 GeV 22 at 1.55 GeV	851	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

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

Updated in March 2018 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 cm ⁻² 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)	H : 210 V : 1	H : 120 V : 3.5	H : 20–45 V : 0.25 → 1	H : 0.5 V : 0.05
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
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)
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: e^+e^- Colliders (III)

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	KEKB (KEK)	PEP-II (SLAC)	SuperKEKB (KEK)
Physics start date	1999	1999	2018
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 ($10^{30} \text{ cm}^{-2}\text{s}^{-1}$)	21083	12069 (design: 3000)	8×10^5
Time between collisions (μs)	0.00590 or 0.00786	0.0042	0.004
Full crossing angle ($\mu \text{ rad}$)	$\pm 11000^*$	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 ($57^\dagger$) (H), 0.61 (V) e^+ : 18 ($55^\dagger$) (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 ($0.27^\dagger$) (H), 0.0059 (V) e^+ : 1.2 ($0.23^\dagger$) (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, p̄p, pp Colliders

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	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)	LHC (CERN)		
Physics start date	1992	1987	2001	2009	2015	2026 (HL-LHC)
Physics end date	2007	2011	—	—		
Particles collided	<i>ep</i>	<i>p̄p̄</i>	<i>pp</i> (polarized)	<i>pp</i>		
Maximum beam energy (TeV)	<i>e</i> : 0.030 p: 0.92	0.980	0.255 55% polarization	4.0	6.5	7.0
Maximum delivered integrated luminosity per exp. (fb ^{−1})	0.8	12	0.38 at 100 GeV 1.3 at 250/255 GeV	23.3 at 4.0 TeV 6.1 at 3.5 TeV	94.5	250/y
Luminosity (10 ³⁰ cm ^{−2} s ^{−1})	75	431	245 (pk) 160 (avg)	7.7 × 10 ³	2 × 10 ⁴	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	300 → 240 [†]	500
Energy spread (units 10 ^{−3})	<i>e</i> : 0.91 p: 0.2	0.14	0.15	0.1445	0.105	0.129
Bunch length (cm)	<i>e</i> : 0.83 p: 8.5	p: 50 p̄: 45	60	9.4	8	9
Beam radius (10 ^{−6} m)	<i>e</i> : 110(<i>H</i>), 30(<i>V</i>) p: 111(<i>H</i>), 30(<i>V</i>)	p: 28 p̄: 16	85	18.8	10	7
Free space at interaction point (m)	±2	±6.5	16	38	38	38
Initial luminosity decay time, − <i>L</i> /(<i>dL/dt</i>) (hr)	10	6 (avg)	7.5	≈ 6	≈ 15	≈ 15 (leveled)
Turn-around time (min)	<i>e</i> : 75, p: 135	90	25	180	150	145
Injection energy (TeV)	<i>e</i> : 0.012 p: 0.040	0.15	0.023	0.450	0.450	0.450
Transverse emittance (10 ^{−9} m)	<i>e</i> : 20(<i>H</i>), 3.5(<i>V</i>) p: 5(<i>H</i>), 5(<i>V</i>)	p: 3 p̄: 1	11	0.59	0.3	0.33
β*, ampl. function at interaction point (m)	<i>e</i> : 0.6(<i>H</i>), 0.26(<i>V</i>) p: 2.45(<i>H</i>), 0.18(<i>V</i>)	0.28	0.65	0.6	0.3	0.15
Beam-beam tune shift per crossing (units 10 ^{−4})	<i>e</i> : 190(<i>H</i>), 450(<i>V</i>) p: 12(<i>H</i>), 9(<i>V</i>)	p: 120 p̄: 120	73	72	45	86
RF frequency (MHz)	<i>e</i> : 499.7 p: 208.2/52.05	53	accel: 9 store: 28	400.8	400.8	400.8
Particles per bunch (units 10 ¹⁰)	<i>e</i> : 3 p: 7	p: 26 p̄: 9	18.5	16	12.5	22
Bunches per ring per species	<i>e</i> : 189 p: 180	36	111	1380	1868 1868 (i.r. 1/5 [‡])	2760 2748 (i.r. 1/5 [‡])
Average beam current per species (mA)	<i>e</i> : 40 p: 90	p: 70 p̄: 24	257	400	420	1100
Circumference (km)	6.336	6.28	3.834	26.659		
Interaction regions	2 colliding beams 1 fixed target (<i>e</i> beam)	2 high $\mathcal{L}$	6 total, 2 high $\mathcal{L}$	4 total, 2 high $\mathcal{L}$		
Magnetic length of dipole (m)	<i>e</i> : 9.185 p: 8.82	6.12	9.45	14.3		
Length of standard cell (m)	<i>e</i> : 23.5 p: 47	59.5	29.7	106.90		
Phase advance per cell (deg)	<i>e</i> : 60 p: 90	67.8	84	90		
Dipoles in ring	<i>e</i> : 396 p: 416	774	192 per ring + 12 common	1232 main dipoles		
Quadrupoles in ring	<i>e</i> : 580 p: 280	216	246 per ring	482 2-in-1 24 1-in-1		
Magnet types	<i>e</i> : C-shaped p: s.c., collared, warm iron	s.c., cos θ warm iron	s.c., cos θ cold iron	s.c., 2 in 1 cold iron		
Peak magnetic field (T)	<i>e</i> : 0.274, p: 5	4.4	3.5	8.3 [§]		

*Other TEVATRON parameters: p̄ source accum. rate: 25×10¹⁰ hr^{−1}; max. no. of p̄ stored: 3.4×10¹² (Accumulator), 6.1×10¹² (Recycler).

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

‡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

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	RHIC (Brookhaven)		LHC (CERN)			
Physics start date	2000	2012 / 2012 / 2004 / 2014 2002 / 2015 / 2015	2010	2012	2017	≥ 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	Xe Xe	Pb Pb
Maximum beam energy (TeV/n)	0.1	0.1	2.51	p: 6.5 Pb: 2.56	2.72	2.76
$\sqrt{s_{NN}}$ (TeV)	0.2	0.2	5.02	8.16	5.44	5.5
Max. delivered int. nucleon-pair lumin. per exp. (pb ⁻¹)	2639 (at 100 GeV/n)	21 / 167 / 60 / 43 169 / 124 / 63 (all at 100 GeV/n)	30.3	194	0.05	$\approx 150/y$
Luminosity (10 ²⁷ cm ⁻² s ⁻¹)	pk: 15.5 avg: 8.7	pk: 0.4 / 12 / 21 / 170 850 / 880 / 7600 avg: 0.6 / 10 / 8 / 100 500 / 450 / 3800	3.6	900	0.4	6 (leveled)
Time between collisions (ns)	107	107 / 107 / 321 / 107 107 / 107 / 107	99.8 / 149.7	99.8 / 149.7	≈ 5500	49.9
Full crossing angle (μ rad)	0	0	290	280	300	> 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	11	7.9
Beam radius (10 ⁻⁶ m)	114*	123* / 163* / 145* / 136* 124* / 147* / 128*	55	19	12	16
Free space at interaction point (m)	16	16	38	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	1	-0.35 [‡] / $\infty^{\ddagger}$ / 1.8 / 0.6 $\infty^{\ddagger}$ / 0.5 / 0.25	2.6	≈ 2	≈ 6	∞
Turn-around time (min)	30	60 / 160 / 90 / 45 90 / 60 / 50	≈ 180	150	180	≈ 180
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* / 38* / 23* / 19* 22* / 26* / 21*	1.5	0.29	0.3	0.5
β^* , ampl. function at interaction point (m)	0.7	0.7 / 0.7 / 0.9 / 1.0 0.7 / 0.8 / 0.8	0.8	0.5	0.4	0.5
Beam-beam tune shift per crossing (units 10 ⁻⁴)	39 [†]	6 [†] / 14 [†] (Cu), 14 [†] (Au) / 30 [†] 42 [†] (h), 22 [†] (Au) / 40 [†] (d), 27 [†] (Au) 53 [†] (p), 41 [†] (Au) / 80 [†] (p) 59 [†] (Au)	9	15	≈ 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)	0.20	0.03 / 0.4 (Cu), 0.13 (Au) / 0.45 4.5 (h), 0.13 (Au) / 13 (d), 0.20 (Au) 22.5 (p), 0.16 (Au) / 24 (p), 1.1 (Al)	0.019 (r.m.s.)	p: 2.6 Pb: 0.022	0.027	0.017
Bunches per ring per species	111	111 / 111 / 37 / 111 111 / 111 / 111	518	p: 540 Pb: 684	16	≈ 1100
Average beam current per species (mA)	224	38 / 160 (Cu), 138 (Au) / 60 125 (h), 143 (Au) / 181 (d), 213 (Au) 313 (p), 176 (Au) / 334 (p), 199 (Al)	14.9	p: 16 Pb: 15	0.54	28
Circumference (km)	3.834		26.659			
Interaction regions	6 total, 2 high $\mathcal{L}$		3 high $\mathcal{L}$ + 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			

*Initial value, smaller after cooling

[†]Initial value, possibly larger after cooling

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

[§]High luminosity upgrade expected ≥ 2021 ; will extend throughout HL-LHC running. Very preliminary, conservative estimates.