

## 32. High-Energy Collider Parameters

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

**Table 32.1:** Updated in March 2022 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<br>(Novosibirsk)     | VEPP-4M<br>(Novosibirsk) | BEPC<br>(China)                    | BEPC-II<br>(China)                     | DAΦNE<br>(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. ( $\text{fb}^{-1}$ ) | 0.25                           | 0.05                     | 0.11                               | 34.5                                   | $\approx 4.7$ in 2001-2007<br>$\approx 2.7$ w/crab-waist<br>$\approx 6.8$ since Nov 2014 |
| Luminosity ( $10^{30} \text{ cm}^{-2}\text{s}^{-1}$ )         | 50                             | 20                       | 12.6 at 1.843 GeV<br>5 at 1.55 GeV | 1000                                   | 453  |
| Time between collisions ( $\mu\text{s}$ )                     | 0.04                           | 0.6                      | 0.8                                | 0.008                                  | 0.0027   |
| Full crossing angle ( $\mu$ rad)                              | 0                              | 0                        | 0                                  | $2.2 \times 10^4$                      | $5 \times 10^4$  |
| Energy spread (units $10^{-3}$ )                              | 0.71                           | 1                        | 0.58 at 2.2 GeV                    | 0.52                                   | 0.40   |
| Bunch length (cm)   | 4                              | 5                        | $\approx 5$                        | $\approx 1.2$                          | low current: 1<br>at 15mA: 2   |
| Beam radius ( $10^{-6}$ m)                                    | 125 (round)                    | H:1000<br>V:30           | H:890<br>V:37                      | H:347<br>V:4.5                         | H:260<br>V:4.8   |
| Free space at interaction point (m)                           | $\pm 0.5$                      | $\pm 2$                  | $\pm 2.15$                         | $\pm 0.63$                             | $\pm 0.295$  |
| Luminosity lifetime (hr)                                      | continuous                     | 2                        | 7–12                               | 1.5                                    | 0.2  |
| Turn-around time (min)  | continuous                     | 18                       | 32                                 | 4 (topping up)                         | 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<br>V:150                 | H:200<br>V:20            | H:660<br>V:28                      | H:121<br>V:1.56                        | H:260<br>V:2.6   |
| $\beta^*$ , amplitude function at interaction point (m)       | H:0.05 - 0.11<br>V:0.05 - 0.11 | H:0.75<br>V:0.05         | H:1.2<br>V:0.05                    | H:1.0<br>V:0.0129                      | H:0.26<br>V:0.009  |
| Beam-beam tune shift per crossing (units $10^{-4}$ )          | H:850<br>V:850                 | 500                      | 350                                | 383                                    | 440/894<br>(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<br>11 at 1.55 GeV      | 3.8                                    | $e^-$ : 3.2<br>$e^+$ : 2.1   |
| Bunches per ring per species                                  | 1                              | 2                        | 1                                  | 119                                    | 100 to 110<br>(120 buckets)  |
| Average beam current per species (mA)                         | 160                            | 80                       | 40 at 2 GeV<br>22 at 1.55 GeV      | 851                                    | $e^-$ : 1250<br>$e^+$ : 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<br>inner ring: 1.41    | outer ring: 1.2<br>inner ring: 1   |
| Length of standard cell (m)                                   | 12                             | 7.2                      | 6.6                                | outer ring: 6.6<br>inner ring: 6.2     | n/a  |
| Phase advance per cell (deg)                                  | H:745<br>V:385                 | 65                       | $\approx 60$                       | 60–90<br>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<br>at 2.8 GeV                | outer ring: 0.677<br>inner ring: 0.766 | 1.2  |

## 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<br>(Cornell)                      | CESR-C<br>(Cornell)  | LEP<br>(CERN)   | SLC<br>(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 ( $\text{fb}^{-1}$ ) | 41.5                                   | 2.0  | 0.221 at Z peak<br>0.501 at 65 – 100 GeV<br>0.275 at >100 GeV | 0.022                       |
| Luminosity ( $10^{30} \text{ cm}^{-2}\text{s}^{-1}$ )               | 1280 at<br>5.3 GeV                     | 76 at<br>2.08 GeV  | 24 at Z peak<br>100 at > 90 GeV                               | 2.5                         |
| Time between collisions ( $\mu\text{s}$ )                           | 0.014 to 0.22                          | 0.014 to 0.22  | 22  | 8300                        |
| Full crossing angle ( $\mu$ rad)                                    | $\pm 2000$                             | $\pm 3300$   | 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 ( $\mu\text{m}$ )                                       | H:460<br>V:4                           | H:340<br>V:6.5   | H:200→300<br>V:2.5→8  | H:1.5<br>V:0.5              |
| Free space at interaction point (m)                                 | $\pm 2.2$ ( $\pm 0.6$<br>to REC quads) | $\pm 2.2$ ( $\pm 0.3$<br>to PM quads)                                | $\pm 3.5$   | $\pm 2.8$                   |
| Luminosity lifetime (hr)  | 2–3                                    | 2–3  | 20 at Z peak<br>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<br>1                               | 120<br>3.5   | H:20–45<br>V:0.25→1   | H:0.5<br>V:0.05             |
| $\beta^*$ , amplitude function at interaction point (m)             | 1.0<br>0.018                           | 0.94<br>0.012  | 1.5<br>0.05   | 0.0025<br>0.0015            |
| Beam-beam tune shift per crossing ( $10^{-4}$ ) or disruption       | 250<br>620                             | $e^-$ : 420 ( $H$ ), 280 ( $V$ )<br>$e^+$ : 410 ( $H$ ), 270 ( $V$ ) | 830   | 0.75 ( $H$ )<br>2.0 ( $V$ ) |
| RF frequency (MHz)  | 500                                    | 500  | 352.2   | 2856                        |
| Particles per bunch (units $10^{10}$ )                              | 1.15                                   | 4.7  | 45 in collision<br>60 in single beam                          | 4.0                         |
| Bunches per ring per species  | 9 trains<br>of 5 bunches               | 8 trains<br>of 3 bunches   | 4 trains of 1 or 2  | 1                           |
| Average beam current per species (mA)                               | 340                                    | 72   | 4 at Z peak<br>4→6 at > 90 GeV                                | 0.0008                      |
| Beam polarization (%)   | —                                      | —  | 55 at 45 GeV<br>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<br>standard cell)            | 45–90 (no<br>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<br>at 8 GeV                  | 0.3 / 0.8 at 8 GeV,<br>2.1 wigglers at 1.9 GeV                       | 0.135   | 0.597                       |

High-Energy Collider Parameters:  $e^+e^-$  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 SuperKEKEB 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.

|   | KEKB<br>(KEK)  | PEP-II<br>(SLAC)   | SuperKEKB<br>(KEK)   |
|---|--|--|--|
| Physics start date  | 1999   | 2008   | 2018   |
| Physics end date  | 2010   | 2008   | —  |
| Maximum beam energy (GeV)                                     | $e^-$ : 8.33 (8.0 nominal)<br>$e^+$ : 3.64 (3.5 nominal)   | $e^-$ : 7–12 (9.0 nominal)<br>$e^+$ : 2.5–4 (3.1 nominal)                  | $e^-$ : 7<br>$e^+$ : 4   |
| Delivered integrated luminosity per exp. ( $\text{fb}^{-1}$ ) | 1040   | 557  | 307  |
| Luminosity ( $10^{30} \text{ cm}^{-2}\text{s}^{-1}$ )         | 21083  | 12069<br>(design: 3000)  | $3.81 \times 10^4$   |
| Time between collisions ( $\mu\text{s}$ )                     | 0.00590 or 0.00786   | 0.0042   | 0.0065   |
| Full crossing angle ( $\mu$ rad)                              | $\pm 11000^*$  | 0  | $\pm 41500$  |
| 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  | $e^-/e^+$ : 0.6/0.6  |
| Beam radius ( $\mu\text{m}$ )                                 | H: 124 ( $e^-$ ), 117 ( $e^+$ )<br>V: 1.9  | 157<br>4.7   | $e^-$ : 16.6 ( $H$ ), 0.24 ( $V$ )<br>$e^+$ : 17.9 ( $H$ ), 0.24 ( $V$ )                               |
| Free space at interaction point (m)                           | +0.75/−0.58<br>(+300/−500) mrad cone   | $\pm 0.2$ ,<br>$\pm 300$ mrad cone   | $e^-$ : +1.20/−1.28, $e^+$ : +0.78/−0.73<br>(+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 ( $V$ )<br>$e^+$ : 18 ( $55^\dagger$ ) ( $H$ ), 0.56 ( $V$ )           | $e^-$ : 48 ( $H$ ), 1.8 ( $V$ )<br>$e^+$ : 24 ( $H$ ), 1.8 ( $V$ )         | $e^-$ : 4.6 ( $H$ ), 0.058 ( $V$ )<br>$e^+$ : 4.0 ( $H$ ), 0.058 ( $V$ )                               |
| $\beta^*$ , amplitude function at interaction point (m)       | $e^-$ : 1.2 (0.27 $^\dagger$ ) ( $H$ ), 0.0059 ( $V$ )<br>$e^+$ : 1.2 (0.23 $^\dagger$ ) ( $H$ ), 0.0059 ( $V$ ) | $e^-$ : 0.50 ( $H$ ), 0.012 ( $V$ )<br>$e^+$ : 0.50 ( $H$ ), 0.012 ( $V$ ) | $e^-$ : 0.060 ( $H$ ), $1 \times 10^{-3}$ ( $V$ )<br>$e^+$ : 0.080 ( $H$ ), $1 \times 10^{-3}$ ( $V$ ) |
| Beam-beam tune shift per crossing (units $10^{-4}$ )          | $e^-$ : 1020 ( $H$ ), 900 ( $V$ )<br>$e^+$ : 1270 ( $H$ ), 1290 ( $V$ )  | $e^-$ : 703 ( $H$ ), 498 ( $V$ )<br>$e^+$ : 510 ( $H$ ), 727 ( $V$ )       | $e^-$ : 15 ( $H$ ), 315 ( $V$ )<br>$e^+$ : 27 ( $H$ ), 433 ( $V$ )                                     |
| 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  | $e^-/e^+$ : 2.76/3.52  |
| Bunches per ring per species                                  | 1585   | 1732   | 1476   |
| Average beam current per species (mA)                         | $e^-/e^+$ : 1188/1637  | $e^-/e^+$ : 1960/3026  | $e^-/e^+$ : 640/819  |
| 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.

$^\dagger$ With dynamic beam-beam effect.

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

**Table 32.4:** Updated in March 2022 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.

|  | HERA<br>(DESY)                                      | TEVATRON*<br>(Fermilab)         | RHIC<br>Brookhaven                    | LHC<br>(CERN)                     |                                       |                                       |
|--|---|---------------------------------|---------------------------------------|-----------------------------------|---------------------------------------|---------------------------------------|
|  | 1992  | 1987                            | 2001                                  | 2009                              | 2015                                  | 2029 (HL-LHC)                         |
| Physics start date   | 1992  | 1987                            | 2001                                  | 2009                              | 2015                                  | 2029 (HL-LHC)                         |
| Physics end date   | 2007  | 2011                            | —                                     | —                                 | —                                     | —                                     |
| Particles collided   | $ep$  | $p\bar{p}$                      | $pp$ (polarized)                      | $pp$                              |                                       |                                       |
| Maximum beam energy (TeV)  | $e$ : 0.030<br>$p$ : 0.92                           | 0.980                           | 0.255<br>55% polarization             | 4.0                               | 6.5                                   | 7.0                                   |
| Max. delivered integrated luminosity per exp. ( $\text{fb}^{-1}$ ) | 0.8   | 12                              | 0.38 at 100 GeV<br>1.3 at 250/255 GeV | 23.3 at 4.0 TeV<br>6.1 at 3.5 TeV | 160                                   | 250/y                                 |
| Luminosity ( $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ )            | 75  | 431                             | 245 (pk)<br>160 (avg)                 | $7.7 \times 10^3$                 | $2.1 \times 10^4$                     | $5.0 \times 10^4$<br>(leveled)        |
| Time between collisions (ns)                                       | 96  | 396                             | 107                                   | 49.90                             | 24.95                                 | 24.95                                 |
| Full crossing angle ( $\mu$ rad)                                   | 0   | 0                               | 0                                     | 290                               | 320 $\rightarrow$ 260 <sup>†</sup>    | 500                                   |
| Energy spread (units $10^{-3}$ )                                   | $e$ : 0.91<br>$p$ : 0.2                             | 0.14                            | 0.15                                  | 0.1445                            | 0.105                                 | 0.129                                 |
| Bunch length (cm)  | $e$ : 0.83<br>$p$ : 8.5                             | $p$ : 50<br>$\bar{p}$ : 45      | 60                                    | 9.4                               | 8                                     | 9                                     |
| Beam radius ( $10^{-6}$ m)   | $e$ : 110 (H), 30 (V)<br>$p$ : 111 (H), 30 (V)      | $p$ : 28<br>$\bar{p}$ : 16      | 85                                    | 18.8                              | 8.5 <sup>‡</sup>                      | 7 <sup>‡</sup>                        |
| Free space at interaction point (m)                                | $\pm 2$   | $\pm 6.5$                       | 16                                    | 38                                | 38                                    | 38                                    |
| Initial luminosity decay time, $-L/(dL/dt)$ (hr)                   | 10  | 6 (avg)                         | 7.5                                   | $\approx 6$                       | $\approx 8$                           | $\approx 7.5$ (leveled)               |
| Turn-around time (min)   | $e$ : 75, $p$ : 135                                 | 90                              | 25                                    | 180                               | 150                                   | 145                                   |
| Injection energy (TeV)   | $e$ : 0.012<br>$p$ : 0.040                          | 0.15                            | 0.023                                 | 0.450                             | 0.450                                 | 0.450                                 |
| Transverse emittance ( $10^{-9}$ m)                                | $e$ : 20 (H), 3.5 (V)<br>$p$ : 5 (H), 5 (V)         | $p$ : 3<br>$\bar{p}$ : 1        | 11                                    | 0.59                              | 0.29                                  | 0.33                                  |
| $\beta^*$ , ampl. function at interaction point (m)                | $e$ : 0.6 (H), 0.26 (V)<br>$p$ : 2.45 (H), 0.18 (V) | 0.28                            | 0.65                                  | 0.6                               | 0.3 $\rightarrow$ 0.25 <sup>§</sup>   | 0.6 $\rightarrow$ 0.15 <sup>§</sup>   |
| Beam-beam tune shift per crossing (units $10^{-4}$ )               | $e$ : 190 (H), 450 (V)<br>$p$ : 12 (H), 9 (V)       | $p$ : 120 $\bar{p}$ : 120       | 73                                    | 72                                | 45                                    | 86                                    |
| RF frequency (MHz)   | $e$ : 499.7<br>$p$ : 208.2/52.05                    | 53                              | accel: 9<br>store: 28                 | 400.8                             | 400.8                                 | 400.8                                 |
| Particles per bunch (units $10^{10}$ )                             | $e$ : 3<br>$p$ : 7                                  | $p$ : 26<br>$\bar{p}$ : 9       | 18.5                                  | 16                                | 11                                    | 22                                    |
| Bunches per ring per species                                       | $e$ : 189<br>$p$ : 180                              | 36                              | 111                                   | 1380                              | 2556<br>2544 (i.r. 1/5 <sup>¶</sup> ) | 2760<br>2748 (i.r. 1/5 <sup>¶</sup> ) |
| Average beam current per species (mA)                              | $e$ : 40<br>$p$ : 90                                | $p$ : 70<br>$\bar{p}$ : 24      | 257                                   | 400                               | 510                                   | 1100                                  |
| Circumference (km)   | 6.336   | 6.28                            | 3.834                                 | 26.659                            |                                       |                                       |
| Interaction regions  | 2 colliding beams<br>1 fixed target ( $e$ beam)     | 2 high $\mathcal{L}$            | 6 total, 2 high $\mathcal{L}$         | 4 total, 2 high $\mathcal{L}$     |                                       |                                       |
| Magnetic length of dipole (m)                                      | $e$ : 9.185;<br>$p$ : 8.82                          | 6.12                            | 9.45                                  | 14.3                              |                                       |                                       |
| Length of standard cell (m)  | $e$ : 23.5<br>$p$ : 47                              | 59.5                            | 29.7                                  | 106.90                            |                                       |                                       |
| Phase advance per cell (deg)                                       | $e$ : 60<br>$p$ : 90                                | 67.8                            | 84                                    | 90                                |                                       |                                       |
| Dipoles in ring  | $e$ : 396<br>$p$ : 416                              | 774                             | 192 per ring<br>+ 12 common           | 1232<br>main dipoles              |                                       |                                       |
| Quadrupoles in ring  | $e$ : 580<br>$p$ : 280                              | 216                             | 246 per ring                          | 482 2-in-1<br>24 1-in-1           |                                       |                                       |
| Magnet types   | $e$ : C-shaped<br>$p$ : s.c., col., warm iron       | s.c., $\cos\theta$<br>warm iron | s.c., $\cos\theta$<br>cold iron       | s.c., 2-in-1<br>cold iron         |                                       |                                       |
| Peak magnetic field (T)  | $e$ : 0.274; $p$ : 5                                | 4.4                             | 3.5                                   | 8.3 <sup>  </sup>                 |                                       |                                       |

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

<sup>†</sup> Variable crossing angle decreasing during the fill with the reduction in bunch population

<sup>‡</sup> Minimum beam radius during levelling

<sup>§</sup>  $\beta^*$  levelling

<sup>¶</sup> Number of bunches colliding at the interaction regions (i.r.) 1 (ATLAS) and 5 (CMS).

<sup>||</sup> Value for design beam energy of 7 TeV.

## High-Energy Collider Parameters: Heavy Ion Colliders

**Table 32.5:** Updated in March 2022 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<br>(Brookhaven)   |   |  | LHC<br>(CERN)     |                               |                |                             |
|---|------------------------|---|--|-------------------|-------------------------------|----------------|-----------------------------|
|   | 2000                   | 2012 / 2018 / 2018 / 2012 / 2004<br>2021 / 2014 / 2002 / 2015 / 2015  |  | 2010              | 2012                          | 2017           | $\geq 2022$<br>(high lum.)* |
| Physics start date  | 2000                   |   |  | 2010              | 2012                          | 2017           | $\geq 2022$<br>(high lum.)* |
| Physics end date  |                        | —   |  |                   | —                             |                |                             |
| Particles collided  | Au Au                  | U U / Zr Zr / Ru Ru / Cu Au / Cu Cu<br>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   |  | 2.51              | p:6.5<br>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. ( $\text{pb}^{-1}$ ) | 2639<br>(at 100 GeV/n) | 21 / 36 / 36.9 / 167 / 60<br>8.2 / 43 / 169 / 124 / 63<br>(all at 100 GeV/n)  |  | 77.8              | 194                           | 0.05           | $\approx 121/y$             |
| Luminosity ( $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ )               | pk: 15.5<br>avg: 8.7   | pk: 0.4 / 4.8 / 3.8 / 12 / 21<br>450 / 170 / 850 / 880 / 7600<br>avg: 0.6 / 2.2 / 2.1 / 10 / 8<br>230 / 100 / 500 / 450 / 3800  |  | 6.1               | 900                           | 0.4            | 6.4 (leveled)               |
| Time between collisions (ns)  | 107                    | 107 / 107 / 107 / 107 / 321<br>107 / 107 / 107 / 107 / 107  |  | 74.9 / 149.7      | 99.8 / 149.7                  | $\approx 5500$ | 49.9                        |
| Full crossing angle ( $\mu$ rad)                                      | 0                      | 0   |  | 320               | 280                           | 300            | 340                         |
| 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 <sup>†</sup>       | 123 <sup>†</sup> / 87 <sup>†</sup> / 88 <sup>†</sup> / 163 <sup>†</sup> / 145 <sup>†</sup><br>100 <sup>†</sup> / 136 <sup>†</sup> / 124 <sup>†</sup> / 147 <sup>†</sup> / 128 <sup>†</sup>  |  | 21                | 19                            | 12             | 17                          |
| Free space at inter. point (m)  | 16                     | 16  |  | 38                | 38                            | 38             | 38                          |
| Initial luminosity decay time, $-L/(dL/dt)$ (hr)                      | 1                      | $-0.35^{\ddagger} / \infty^{\S} / \infty^{\S} / \infty^{\ddagger} / 1.8$<br>$\infty / 0.6 / \infty^{\ddagger} / 0.5 / 0.25$   |  | 3.3               | $\approx 2$                   | $\approx 6$    | $\infty$                    |
| Turn-around time (min)  | 30                     | 60 <sup>¶</sup> / 40 <sup>¶</sup> / 40 <sup>¶</sup> / 160 <sup>¶</sup> / 90 <sup>¶</sup><br>45 <sup>¶</sup> / 45 <sup>¶</sup> / 90 <sup>¶</sup> / 60 <sup>¶</sup> / 50 <sup>¶</sup>   |  | $\approx 180$     | 150                           | 180            | $\approx 200$               |
| 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 <sup>†</sup>        | 22 <sup>†</sup> / 10.7 <sup>†</sup> / 11.2 <sup>†</sup> / 38 <sup>†</sup> / 23 <sup>†</sup><br>12 <sup>†</sup> / 19 <sup>†</sup> / 22 <sup>†</sup> / 26 <sup>†</sup> / 21 <sup>†</sup>  |  | 0.85              | 0.29                          | 0.3            | 0.5                         |
| $\beta^*$ , ampl. function at interaction point (m)                   | 0.7                    | 0.7 / 0.7 / 0.7 / 0.7 / 0.9<br>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 <sup>†</sup>        | 6 <sup>†</sup> / 18 <sup>†</sup> / 21 <sup>†</sup> / 14 <sup>†</sup> , 14 <sup>†</sup> / 30 <sup>†</sup> / 34 <sup>†</sup><br>42 <sup>†</sup> , 22 <sup>†</sup> / 40 <sup>†</sup> , 27 <sup>†</sup> / 53 <sup>†</sup> , 41 <sup>†</sup> / 80 <sup>†</sup> , 59 <sup>†</sup> |  | 15                | 15                            | $\approx 10$   | 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<br>4.5, 0.13 / 13, 0.20 / 22.5, 0.16 / 24, 1.1   |  | 0.022<br>(r.m.s.) | p:2.6 Pb:0.022                | 0.027          | 0.018                       |
| Bunches per ring per species  | 111                    | 111 / 111 / 111 / 111 / 37<br>106 / 111 / 111 / 111 / 111   |  | 733               | p:540<br>Pb:684               | 16             | 1240                        |
| Average beam current per species (mA)                                 | 224                    | 38 / 56 / 61 / 160,138 / 60 / 95<br>125,143 / 181,213 / 313,176 / 334,199   |  | 23.8              | p:16<br>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<br>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. $\cos \theta$ , cold iron  |  |                   | s.c., 2 in 1, cold iron       |                |                             |
| Peak magnetic field (T)   |                        | 3.5   |  |                   | 8.3                           |                |                             |

\*High luminosity upgrade expected  $\geq 2022$ ; will extend throughout HL-LHC running. Very preliminary, conservative estimates.

<sup>†</sup>Initial value, increases (decreases) without (with) cooling

<sup>‡</sup>Negative or infinite decay time is effect of cooling.

<sup>§</sup>luminosity leveled to flat after set to target value, with cooling

<sup>¶</sup>measured minimum, not theoretical