Physics 610

Adv Particle Physics

April 2, 2014

Physics 610

COURSE DESCRIPTION

Physics 610 continues the survey of the phenomena of the elementary particles of matter and their interactions of Physics 661 and 662.

During this term we will study:

- Experimental Methods
    - Accelerators and Detectors
- Early Universe
- Gravitational Radiation

Physics 610

Course Administration

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and TBD

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Physics 610 web page: http://physics-server.uoregon.edu/~jimbrau/ph610-2014

Grades will be based on problem sets and classroom participation, especially a written and oral project.

Physics 610

TENTATIVE SCHEDULE

- April 2 – April 23 Experimental Methods
  - Martin & Shaw, Chapter 4
  - Particle Data Group – "Experimental Methods and Colliders"
- April 28 – May 7 Early Universe
  - Introduction to Cosmology by Mark Trodden and Sean M. Carroll
  - http://arxiv.org/pdf/astro-ph/0401547v1.pdf
- May 19 - May 28 Gravitational Radiation
  - Physics, Astrophysics and Cosmology with Gravitational Waves by B.S. Sathyaprakash and Bernard F. Schutz
  - http://relativity.livingreviews.org/Articles/lrr-2009-2/download/lrr-2009-2Color.pdf
- June 2-4 Presentations

Accelerators

- History
- Two Principles
  - Electrostatic
    - Cockcroft-Walton
    - Van de Graaff and tandem
      - Van de Graaff
  - Transformers
    - Cyclotron
    - Betatron
    - Linear Induction
- Synchrocyclotron
- Synchrotron
- Phase Stability
- Strong focusing
- Betatron Oscillations
- High-impedence Microwave Devices
- Superconducting Technology
- X-band RF
- Large Colliders

Detectors

<u>Interaction of Charged Particles and Radiation with Matter</u>

- Ionization loss of charged particles
- Coulomb scattering
- Radiation loss by electrons
- Absorption of gamma-rays in Matter

<u>Detectors of Single Charged Particles</u>

- Pictorial Detectors: Cloud Chambers, Emulsions, Streamer Chambers, Spark Chambers, Bubble Chambers
- Proportional counters, Drift chambers, Scintillation counters, Cerenkov counters, Solid-state counters,

<u>Shower Detectors and Calorimeters</u>

- Electromagnetic-shower detectors
- Hadron-shower detectors

Relativity & Cosmology

- Proton Decay and Virtual Black Holes
- Special Relativity
- General Relativity
- The Equivalence Principle
- Gravitational Redshift and the Bending of Light
- Extra Dimensions and Black Holes
- Coordinates and Metric
- Curved Space-time
- Einstein's Equations of Gravitation

- Hubble's law and the expanding universe
- Cosmological Models
- Friedmann equation
- Cosmic microwave radiation: the hot Big Bang
- Radiation and matter eras
- Nucleosynthesis in the Big Bang
- Baryon-antibaryon asymmetry
- Dark matter
- Inflation

Gravitational Radiation

- What is gravitational radiation?
- Indirect evidence for gravitational radiation (the Taylor-Hulse binary neutron star)
- What are the natural sources
- How to build a detector
- LIGO
- Future directions

Project

Schedule

- ASAP – sign up for topic
- April 28 - letter of intent
- May 28 - written proposal
- June 2-4 – oral presentations

Project

Write a proposal and prepare a presentation for an experiment. You may choose from the following, or select another experiment which interests you.

- detection of gravitational waves from compact binary inspiral
- detection of gravitational waves from era of inflation
- produce a billion Z^0 bosons and exploit their decays for many measurements
- improve the top quark mass measurement
- improve the mass measurement of the W
- search for a supersymmetric particle
- search for a new heavy lepton
- search for quark substructure
- measure t anti-t forward-backward asymmetry in hadron-hadron collisions
- study ν_τ interactions
- improve measurements of neutrino oscillations
- search for evidence of sterile neutrinos
- search for the decay $\mu \to e \gamma$
- measure the decay $K^0_L \to \pi^0 \nu$ anti-ν
- measure α_s with precision
- measurement of the Higgs boson total width
- search for leptoquarks

Project

Experiments in high energy physics are approved by laboratory directors after their program committees have made recommendations on the proposals that have been received by the laboratory. The program committee is a group of about a dozen physicists from around the world with expertise and experience broad enough to address the relative importance of the physics goals of the experiment as well as the likelihood that the design of the experiment will succeed.

Your proposal should be a minimum of 6 pages, and no more than 12 pages, of written text, with important figures attached (additional pages).

It should contain:

1. A discussion of the physics goals of the experiment, the present world knowledge of the topic, and its impact on other physics (such as through virtual loop contributions to other measurements). Why is this an important experiment to do?

Project

2. A discussion of the experimental technique. What are the backgrounds? What are the required measurements and resolutions? What are the systematic errors which limit the measurement?
3. A specification of the accelerator facility needed (energy, particles, targets, luminosity, etc.) Will an upgrade of an existing facility be needed, will a new facility be needed, or is the present capability acceptable?
4. Specification of the apparatus. Describe the individual subsystems (such as interferometer, telescope, vertex detector, tracker, particle identification system, calorimeter, and muon system). What is the required level of performance for the systems required in the experiment?
5. Run plan. How many events or hours of observation do you need to acquire? How many days of running will this take? You might want to estimate how many collaborators you will need to pull this off. (Of course this is relevant to the detector work in item 4, as well, unless you are using an existing detector. However, even an existing detector could be rather sophisticated, requiring many collaborators with specialized knowledge.)

Project

(You may find the Particle Data Group web page useful in getting the latest information for your experiment: http://www-pdg.lbl.gov)

After you submit your proposal, you will be required to make a 30-40 minute presentation to the program committee and answer their questions.

A "letter of intent" must be submitted by April 28 indicating the topic you intend to propose with a brief summary. This should be about one page long.

Rules of the Game

You may discuss your proposal among yourselves (I even encourage it) but in the end, you must write your own proposal.

Project

Schedule

- ASAP – sign up for topic
- April 28 - letter of intent (about 1 page)
- May 28 - written proposal (6-12 pages plus figures and tables)
- June 2-4 – oral presentations

Experimental Methods

- Accelerators
  - History
  - Techniques
  - Current Facilities

- Detectors
  - Fundamental principles
  - Detector concepts
  - Current and recent experiments

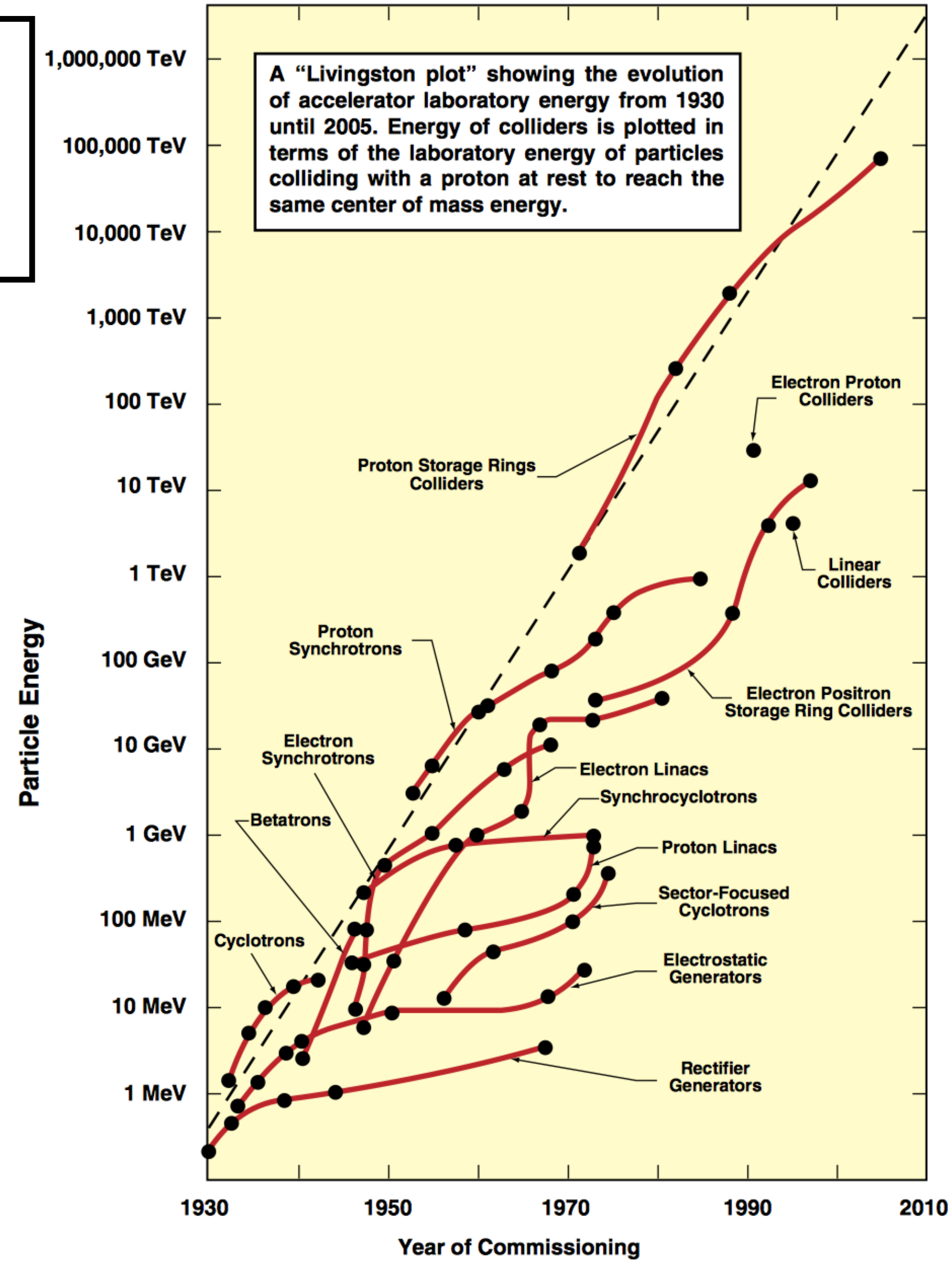
Accelerators

	Location		Energy, GeV
Proton synchrotrons			
CERN PS	Geneva		28
BNL AGS	Brookhaven, Long Island		32
KEK	Tsukuba, Tokyo		12
Serpukhov	USSR		76
SPS	CERN, Geneva		450
Fermilab Tevatron II	Batavia, Illinois		1000
Electron accelerators			
SLAC linac	Stanford, California		25–50
DESY synchrotron	Hamburg		7
Colliding-beam machines			
PETRA	DESY, Hamburg	e^+e^-	$22 + 22$
PEP	Stanford	e^+e^-	$18 + 18$
CESR	Cornell, NY	e^+e^-	$8 + 8$
TRISTAN	Tsukuba	e^+e^-	$30 + 30$
SLC	Stanford	e^+e^-	$50 + 50$
LEP I	CERN	e^+e^-	$50 + 50$
LEP II	CERN	e^+e^-	$100 + 100$
$Sp\bar{p}S$	CERN	$p\bar{p}$	$310 + 310$
Tevatron I	Fermilab	$p\bar{p}$	$1000 + 1000$
HERA	Hamburg	ep	$30e + 820p$
LHC (2005)[a]	CERN	pp	$7000 + 7000$

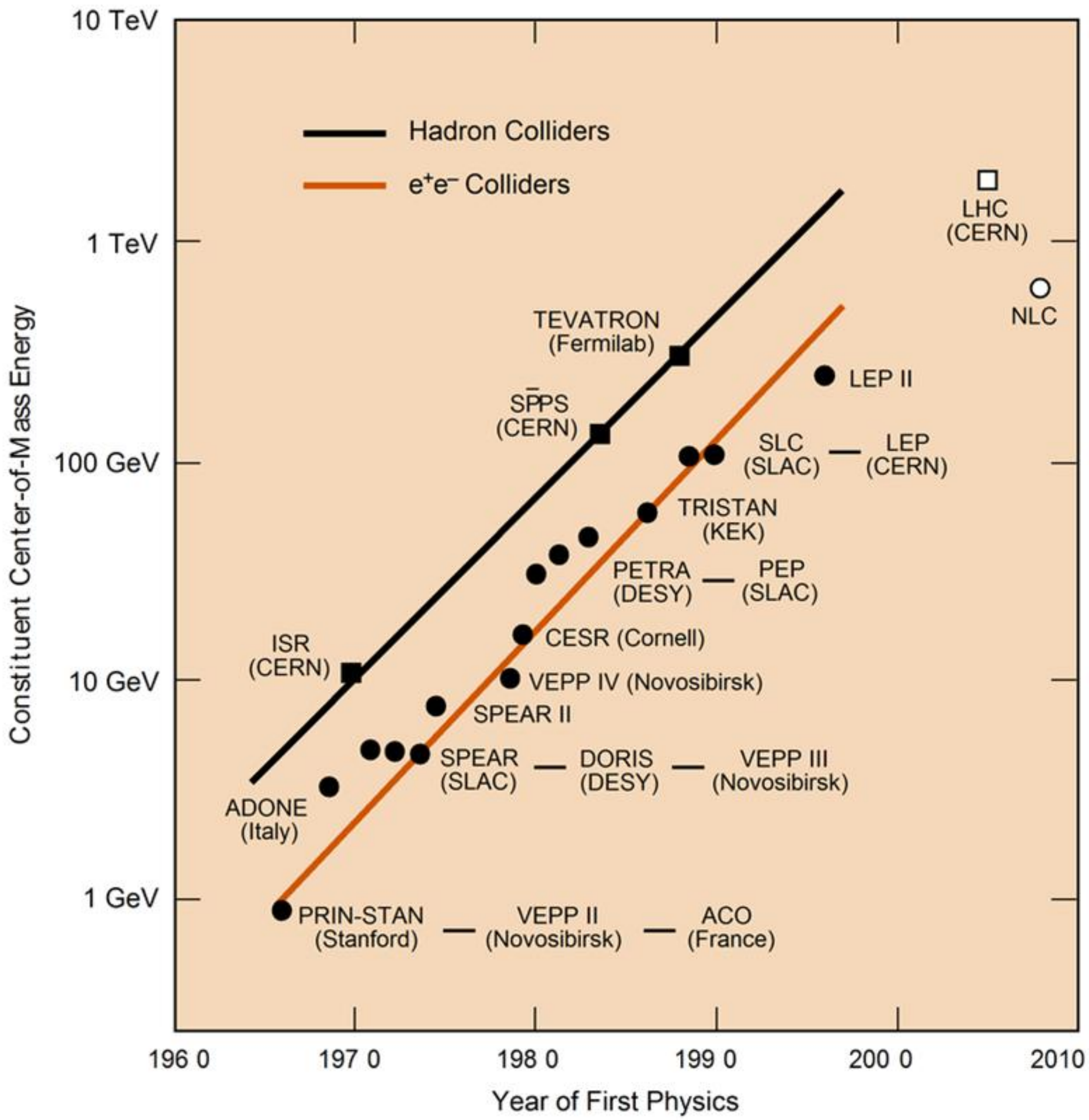
[a] Expected completion date

Historical Development

- Livingston Plot
  - Chao et al.
    Snowmass 2001
    slac-pub-9483

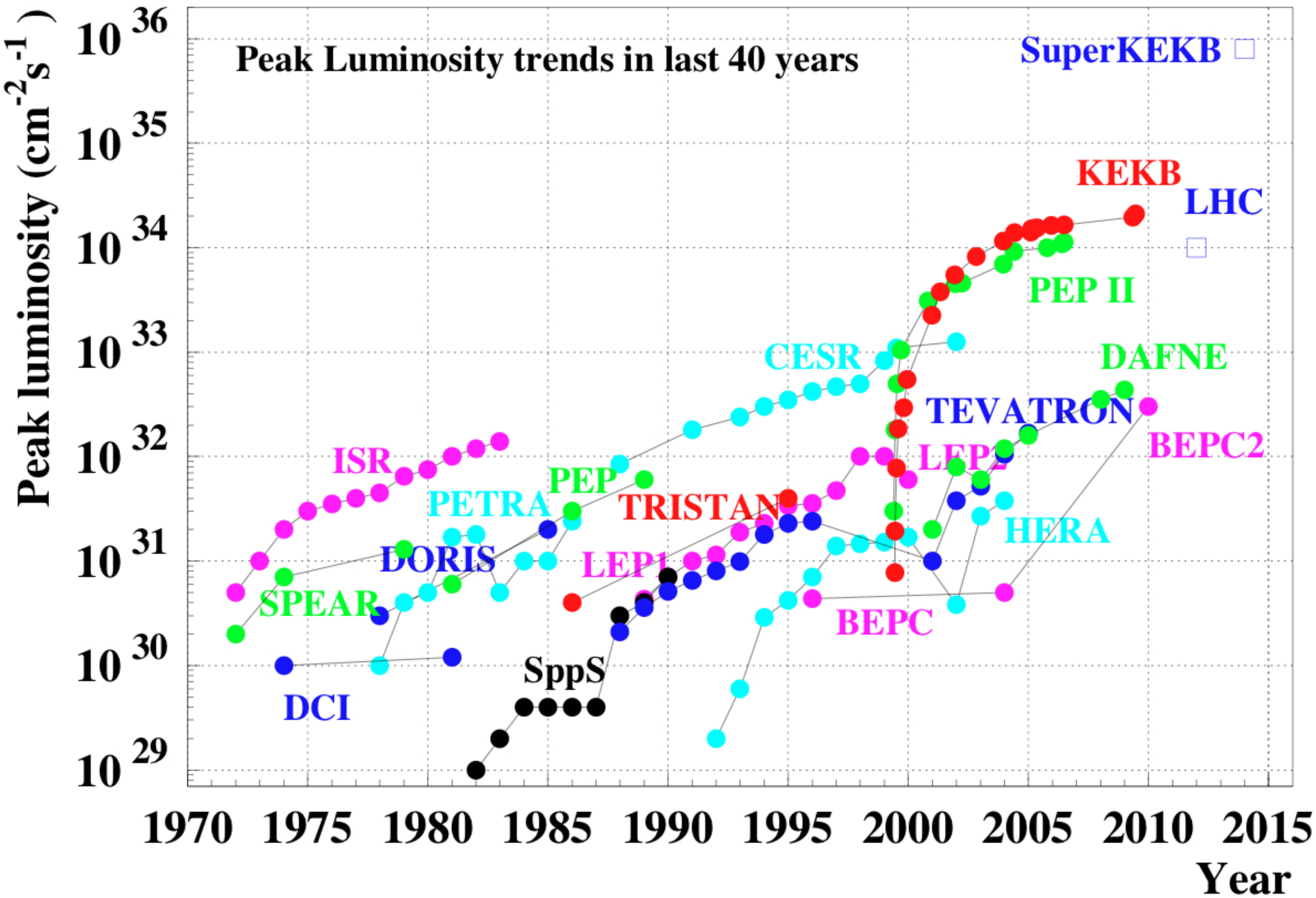


Historical Development



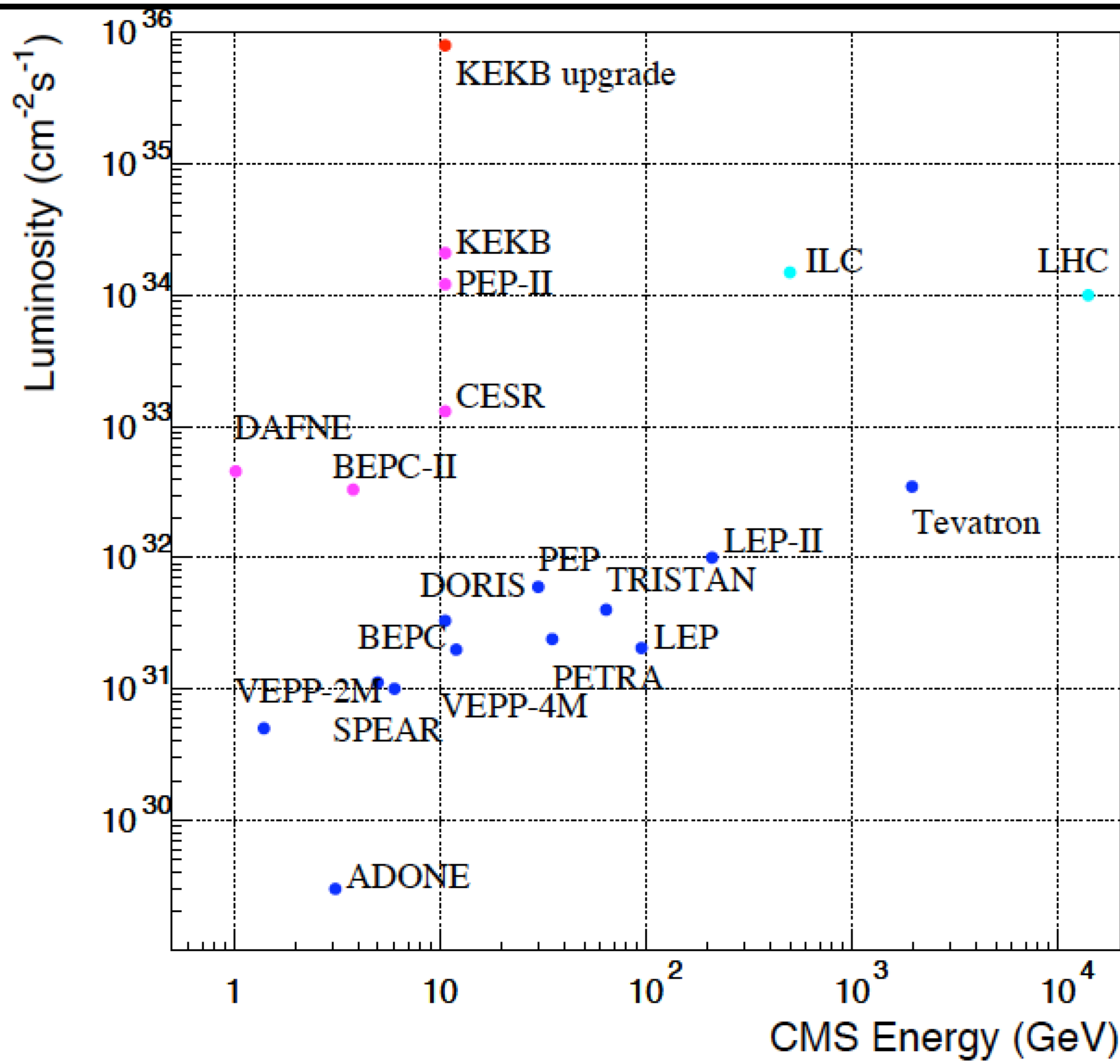
Symmetry Magazine

Historical Development



www-ac.kek.jp

Historical Development



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HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (I)

Updated in September 2013 with numbers received from representatives of the colliders (contact J. Beringer, LBNL). The table shows parameter values as achieved by July 1, 2013. 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	3.74	≈ 4.7 in 2001-2007 2.7 w/crab-waist
Luminosity (10^{30} $cm^{-2}s^{-1}$)	100	20	12.6 at 1.843 GeV 5 at 1.55 GeV	649	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	≈ 5	≈ 1.5	low current: 1 at 15mA: 2
Beam radius (10^{-6} m)	125 (round)	H: 1000 V: 30	H: 890 V: 37	H: 380 V: 5.7	H: 260 V: 4.8
Free space at interaction point (m)	±1	±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	26	2 (topping up)

	VEPP-2000 (Novosibirsk)	VEPP-4M (Novosibirsk)	BEPC (China)	BEPC-II (China)	DAΦNE (Frascati)
Turn-around time (min)	continuous	18	32	26	2 (topping up)
Injection energy (GeV)	0.2–1.0	1.8	1.55	1.89	on energy
Transverse emittance ($10^{-9}\pi$ rad-m)	H: 250 V: 250	H: 200 V: 20	H: 660 V: 28	H: 144 V: 2.2	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: 0.015	H: 0.26 V: 0.009
Beam-beam tune shift per crossing (units 10^{-4})	H: 750 V: 750	500	350	327	440
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	4.1	e^-: 3.2 e^+: 2.1
Bunches per ring per species	1	2	1	88	100 to 105 (120 buckets)
Average beam current per species (mA)	150	80	40 at 2 GeV 22 at 1.55 GeV	725	e^-: 1500 e^+: 1000
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	≈ 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 September 2013 with numbers received from representatives of the colliders (contact J. Beringer, LBNL). For existing colliders, the table shows parameter values as achieved by July 1, 2013. 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: 175)
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	1.5×10^4	6×10^4
Time between collisions (μs)	0.014 to 0.22	0.014 to 0.22	22	8300	$0.55^{\dagger}$	$0.0005^{\ddagger}$
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

	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	SLC (SLAC)	ILC (TBD)	CLIC (TBD)
Injection energy (GeV)	1.8–6	1.5–6	22	45.64	n/a	n/a
Transverse emittance ($10^{-9}\pi$ rad-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	48
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.

‡Time between bunch trains: 20ms.

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

HIGH-ENERGY COLLIDER PARAMETERS: e^+e^- Colliders (III)

Updated in September 2013 with numbers received from representatives of the colliders (contact J. Beringer, LBNL). For existing colliders, the table shows parameter values as achieved by July 1, 2013. 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	2015
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

	KEKB (KEK)	PEP-II (SLAC)	SuperKEKB (KEK)
Injection energy (GeV)	e^-/e^+ : 8.0/3.5 (nominal)	e^-/e^+ : 9.0/3.1 (nominal)	e^-/e^+ : 7/4
Transverse emittance ($10^{-9}\pi$ rad-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, $\overline{p}p$, pp Colliders

Updated in September 2013 with numbers received from representatives of the colliders (contact J. Beringer, LBNL). The table shows parameter values as achieved by July 1, 2013. For LHC, the parameters expected at the ATLAS and CMS experiments for running in 2015 and design values for a high-luminosity upgrade (HL-LHC) are also given. 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; pk and avg denote peak and average values.

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)	LHC (CERN)		
Physics start date	1992	1987	2001	2009	2015 (expected)	2023 (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 57% polarization	4.0	6.5	7.0
Maximum delivered integrated luminosity per exp. (fb^{-1})	0.8	12	0.18 at 100 GeV 0.75 at 250/255 GeV	23.3 at 4.0 TeV 6.1 at 3.5 TeV	40/y to 60/y	250/y
Luminosity (10^{30} $cm^{-2}s^{-1}$)	75	431	215 (pk) 132 (avg)	7.7×10^3	$(1-2) \times 10^4$	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	298	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 $\bar{p}$: 45	60	9.4	9	9
Beam radius (10^{-6} m)	e: $110(H), 30(V)$ p: $111(H), 30(V)$	p: 28 $\bar{p}$: 16	90	18.8	11.1	7.4
Free space at interaction point (m)	±2	±6.5	16	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	10	6 (avg)	5.5	≈ 6	≈ 6	≈ 6 (leveled)
Turn-around time (min)	e: 75, p: 135	90	150	180	240	240

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)	LHC (CERN)		
Injection energy (TeV)	e: 0.012 p: 0.040	0.15	0.023	0.450	0.450	0.450
Transverse emittance ($10^{-9}\pi$ rad-m)	e: $20(H), 3.5(V)$ p: $5(H), 5(V)$	p: 3 $\bar{p}$: 1	15	0.59	0.28	0.36
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	0.45	0.15
Beam-beam tune shift per crossing (units 10^{-4})	e: $190(H), 450(V)$ p: $12(H), 9(V)$	p: 120 $\bar{p}$: 120	70	72	79	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 $\bar{p}$: 9	18.5	16	12	22
Bunches per ring per species	e: 189 p: 180	36	111	1380	2508	2760
Average beam current per species (mA)	e: 40 p: 90	p: 70 $\bar{p}$: 24	257	400	540	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 type	e: C-shaped p: s.c., collared, cold 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: 25×10^{10} hr^{-1}; max. no. of $\overline{p}$ stored: 3.4×10^{12} (Accumulator), 6.1×10^{12} (Recycler).

HIGH-ENERGY COLLIDER PARAMETERS: Heavy Ion Colliders

Updated in September 2013 with numbers received from representatives of the colliders (contact J. Beringer, LBNL). The table shows parameter values as achieved by July 1, 2013. For LHC, the parameters expected at the ALICE experiment for running in 2015 and 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 / 2002	2010	2012	2015 (expected)	$\geq$ 2019 (high lum.)[‡]
Physics end date	—		—			
Particles collided	Au Au	U U / Cu Au / Cu Cu / d Au	Pb Pb	p Pb	Pb Pb	Pb Pb
Maximum beam energy (TeV/n)	0.1	0.1	1.38	*p*: 4 *Pb*: 1.58	2.76	2.76
$\sqrt{s_{NN}}$ (TeV)	0.2	0.2	2.76	5.0	5.5	5.5
Max. delivered int. nucleon-pair lumin. per exp. (pb^{-1})	568 (at 100 GeV/n)	21 / 167 / 65 / 103 (at 100 GeV/n)	7.4	6.6	$\approx 15/y$	$\approx 56/y$
Luminosity (10^{27} $cm^{-2}s^{-1}$)	5.0 (pk) 3.0 (avg)	0.9 / 12 / 20 / 270 (pk) 0.6 / 10 / 0.8 / 140 (avg)	0.5	100 (leveled) 116 (pk ATLAS/CMS)	1 (leveled)	4
Time between collisions (ns)	107	107 / 107 / 321 / 107	199.6	199.6 / 224.6	199.6	49.9
Full crossing angle (μ rad)	0	0	140	120	120	> 160
Energy spread (units 10^{-3})	0.75	0.75	0.11	0.11	0.11	0.11
Bunch length (cm)	30	30	9.7	*p*: 9 *Pb*: 11.5	9.7	7.9
Beam radius (10^{-6} m)	135	50 / 160 / 145 / 145	50	*p*: 19 *Pb*: 27	16	16
Free space at interaction point (m)	16	16	38	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	1.2	-0.35[†]/ ∞[†]/ 1.8 / 1.5	5	≈ 6	n/a (leveled)	3.5
Turn-around time (min)	60	60 / 160 / 90 / 90	180	≈ 240	≈ 180	≈ 180

	RHIC		LHC			
Injection energy (TeV)	0.011 TeV/n	0.011 TeV/n	0.177 TeV/n	*p*: 0.45 TeV/n *Pb*: 0.177 TeV/n	0.177 TeV/n	0.177 TeV/n
Transverse emittance ($10^{-9}\pi$ rad-m)	23	4 / 11 / 23 / 25	1.0	*p*: 0.5 *Pb*: 0.9	0.5	0.5
β^*, ampl. function at interaction point (m)	0.75	0.7 / 0.7 / 0.9 / 0.85	1.0	0.8	0.5	0.5
Beam-beam tune shift per crossing (units 10^{-4})	16	7 / 14 (Cu), 14 (Au) / 30 / 21 (d), 17 (Au)	3	*p*: 9 *Pb*: 10	9	6.7
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})	0.13	0.03 / 0.4 (Cu), 0.13 (Au) / 0.45 / 10 (d), 0.1 Au	0.011 (r.m.s.)	*p*: 1.6 *Pb*: 0.014	0.014	0.01
Bunches per ring per species	111	111 / 111 / 37 / 95	356	338	358	≈ 1100
Average beam current per species (mA)	145	38 / 159 (Cu), 138 (Au) / 60 / 119 (d), 94 Au	6.85	*p*: 9.7 *Pb*: 7	7.4	16
Circumference (km)	3.834		26.659			
Interaction regions	6 total, 2 high $\mathscr{L}$		1 dedicated +2	3 high $\mathscr{L}$ +1	1 dedicated +2	1 dedicated +2
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 (d), 93 (Au)	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 >= 2019; will extend throughout HL-LHC running. Very preliminary, conservative estimates.

Accelerators

- History
- Two Principles
  - Electrostatic
    - Cockcroft-Walton
    - Van de Graaff and tandem Van de Graaff
  - Transformers
    - Cyclotron
    - Betatron
    - Linear Induction Acclerator
- Phase Stability
- Synchrocyclotron
- Synchrotron
- Strong focusing
- High-impedence Microwave Devices
- Superconducting Technology

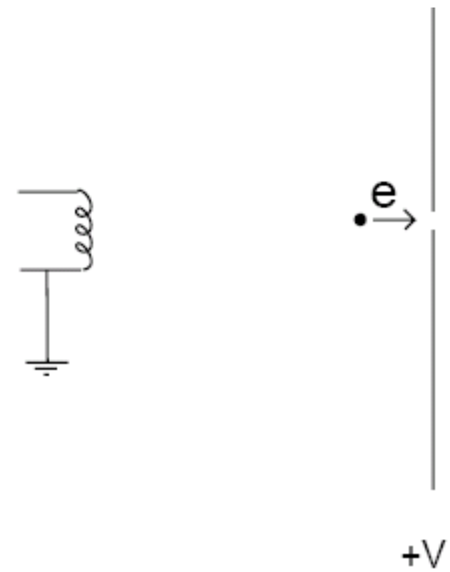
References:
Donald H. Perkins, Introduction to High Energy Physics, Fourth Edition
E.J.N.Wilson, "Physics of Accelerators"

Going to Higher Energy

- There are two motivations for higher energy interactions
  - To produce and discover more massive particles
    - Need more center of mass energy
      - $E = mc^2$
  - To explore smaller dimensions
    - deBroglie wavelength $\lambda = h/p$
    - $p > \hbar/d$
    - $cp > \hbar c/d = 197$ MeV-fm / d

Electron Gun (Cathode Ray Tube)

- Very elementary accelerator
  - Cathode ray tube
- Heated filament liberates electrons
- Electrons accelerated from grounded cathode to anode at potential +V, and shoot through hole in anode, with energy E = qV
- Energy acquired defined in eV
  - 1 eV = 1.6×10^{-19} Joules
- Energy limited by breakdown voltage of a few MV



Early History of Accelerators

- 1931 - Van de Graaff
- 1932 - Cockroft-Walton
- 1932 - cyclotron
  - Lawrence and Livingston
- 1940 - betatron
  - Wideroe/Kerst
- 1944/45 - phase stability
  - McMillan and Veksler
- 1950/52 -strong focusing
  - Christofilos/ Courant, Livingston, and Snyder

Two Principle Approaches

- Electrostatic
  - particles traverse a difference in electric potential

    or

- Transformer
  - high-current, low-voltage circuit element used to supply energy to a high-voltage, low-current accelerating path

W.K.H. Panofsky and M. Breidenbach, Rev. Mod. Phys. 71, S122

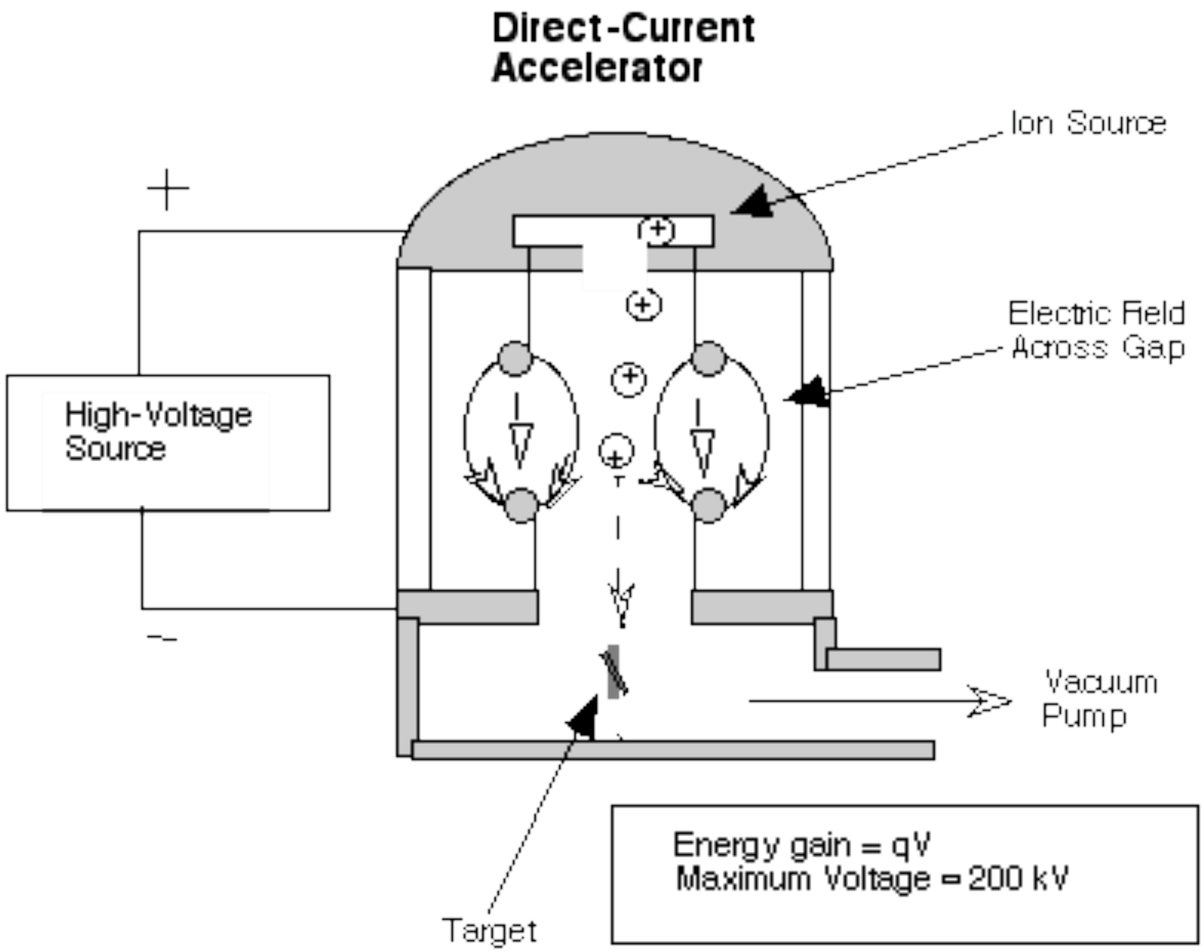
Electrostatic

- The limitation of the electrostatic approach comes from the ultimate breakdown of high voltages

  - Cockroft-Walton (1932)
    - charge capacitors in parallel and connect in series
  - Van de Graaff (1931)
    - charges sprayed onto moving belt and removed inside a high-voltage electrode

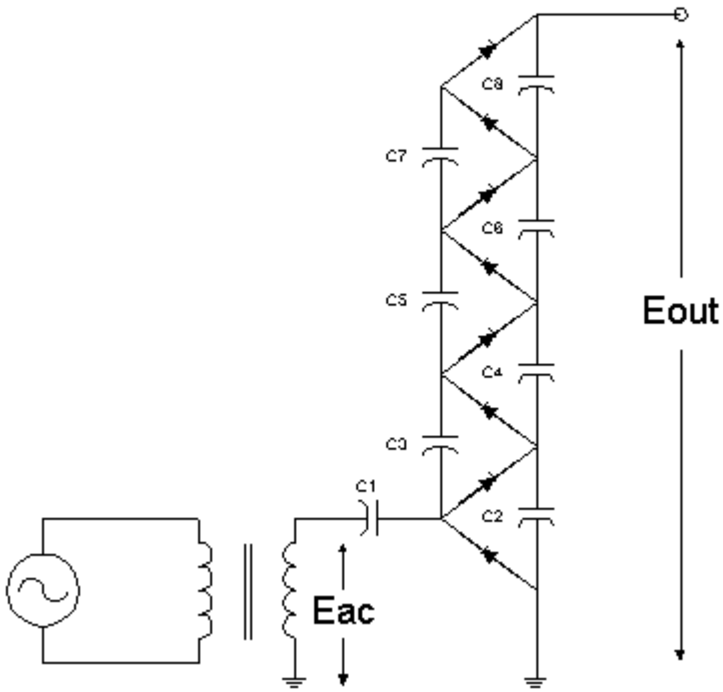
W.K.H. Panofsky and M. Breidenbach, Rev. Mod. Phys. 71, S122

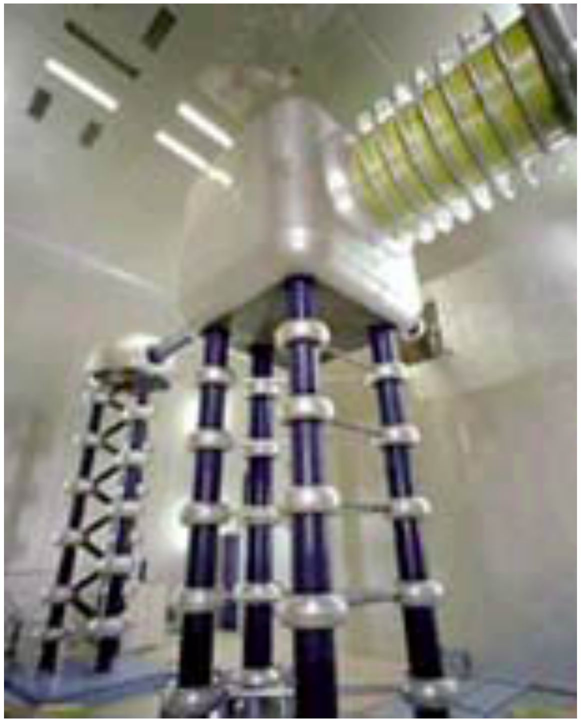
Cockcroft-Walton



Cockcroft-Walton

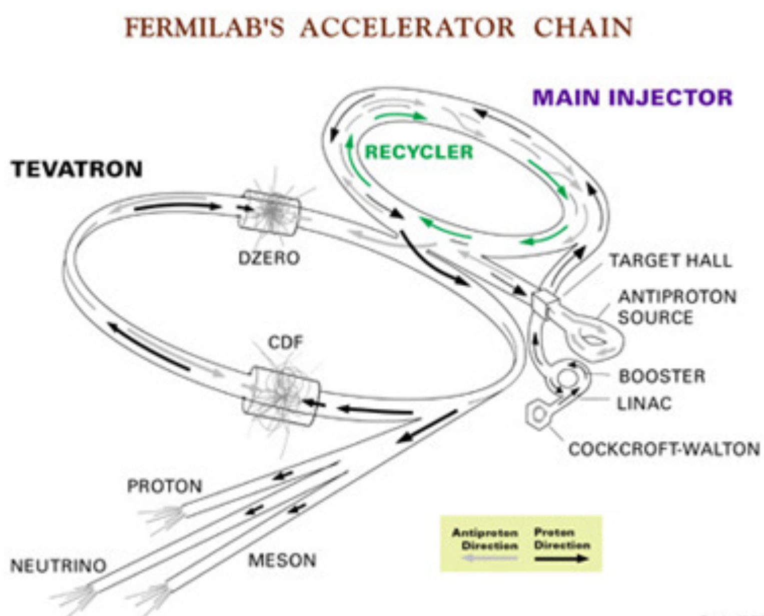
- Cockroft-Walton (1932)
  - charge capacitors in parallel and connect in series

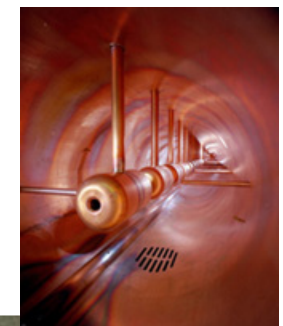




- first stage of Fermilab complex is Cockroft-Walton

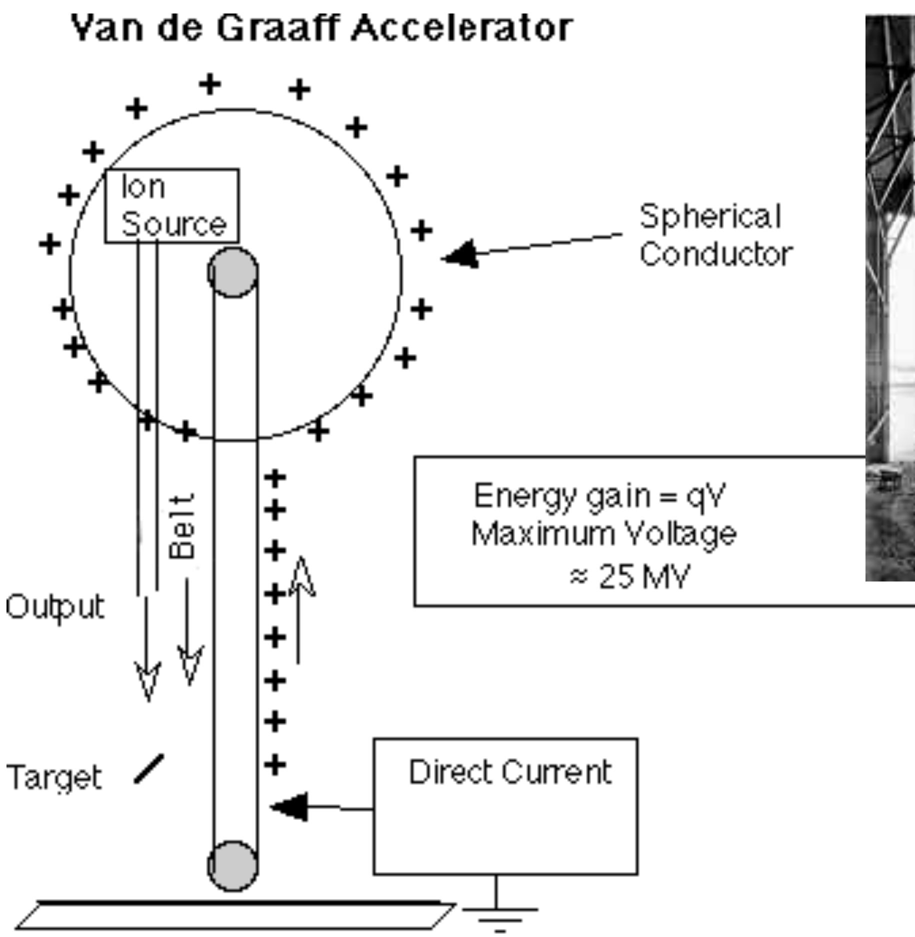
Fermilab's chain of accelerators





- Cockcroft-Walton 750 keV
- Linac 400 MeV
- Booster 8 GeV
- Main Injector 150 GeV
- TeVatron 1 TeV

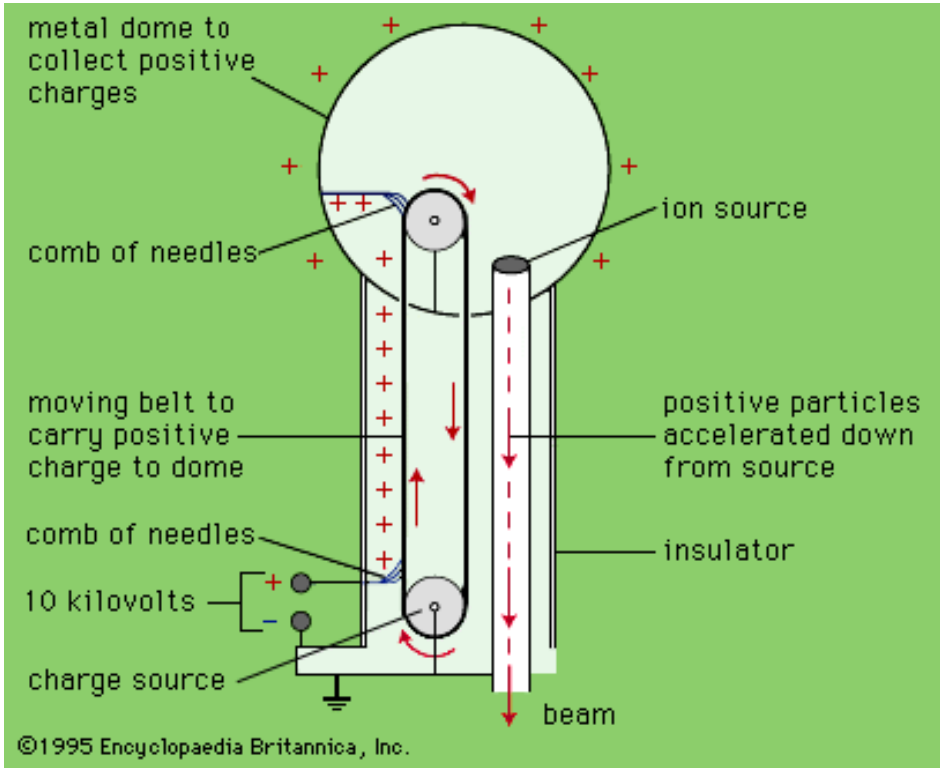
Van de Graaff



Developed in the 30's

Electrostatic

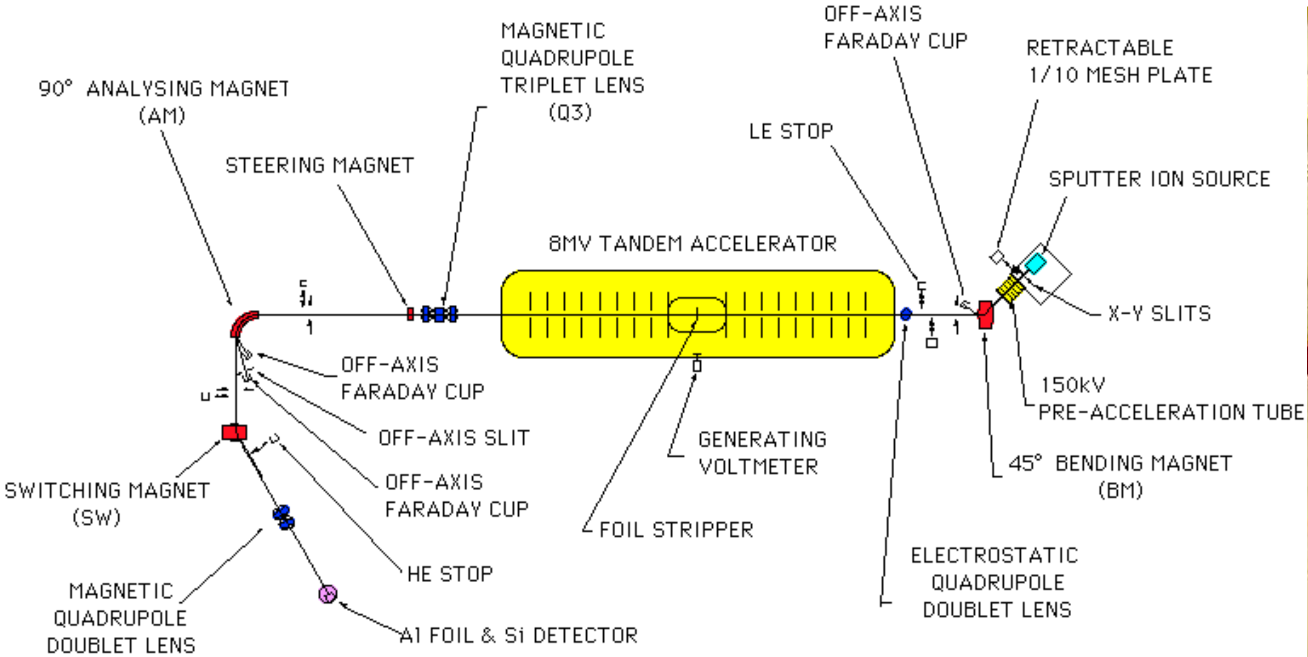
- Van de Graaff (1931)
  - charges sprayed onto moving belt and removed inside a high-voltage electrode



Ref: E. Wilson, CERN

Tandem Van de Graaff

- Introduced in the 50's
  - accelerate negative ions, strip, and accelerate positive ions



Transformer

- Electrostatic approaches fail above about 10 MeV
- Linear Accelerator
- Cyclotron
  - orbital period of nonrelativistic particles circulating in a uniform magnetic field is independent of energy
- Betatron
  - electrons become relativistic at moderate energies, and cyclotron fails