Experimental Techniques

- Accelerators
  - History
  - Techniques
  - Current Facilities

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

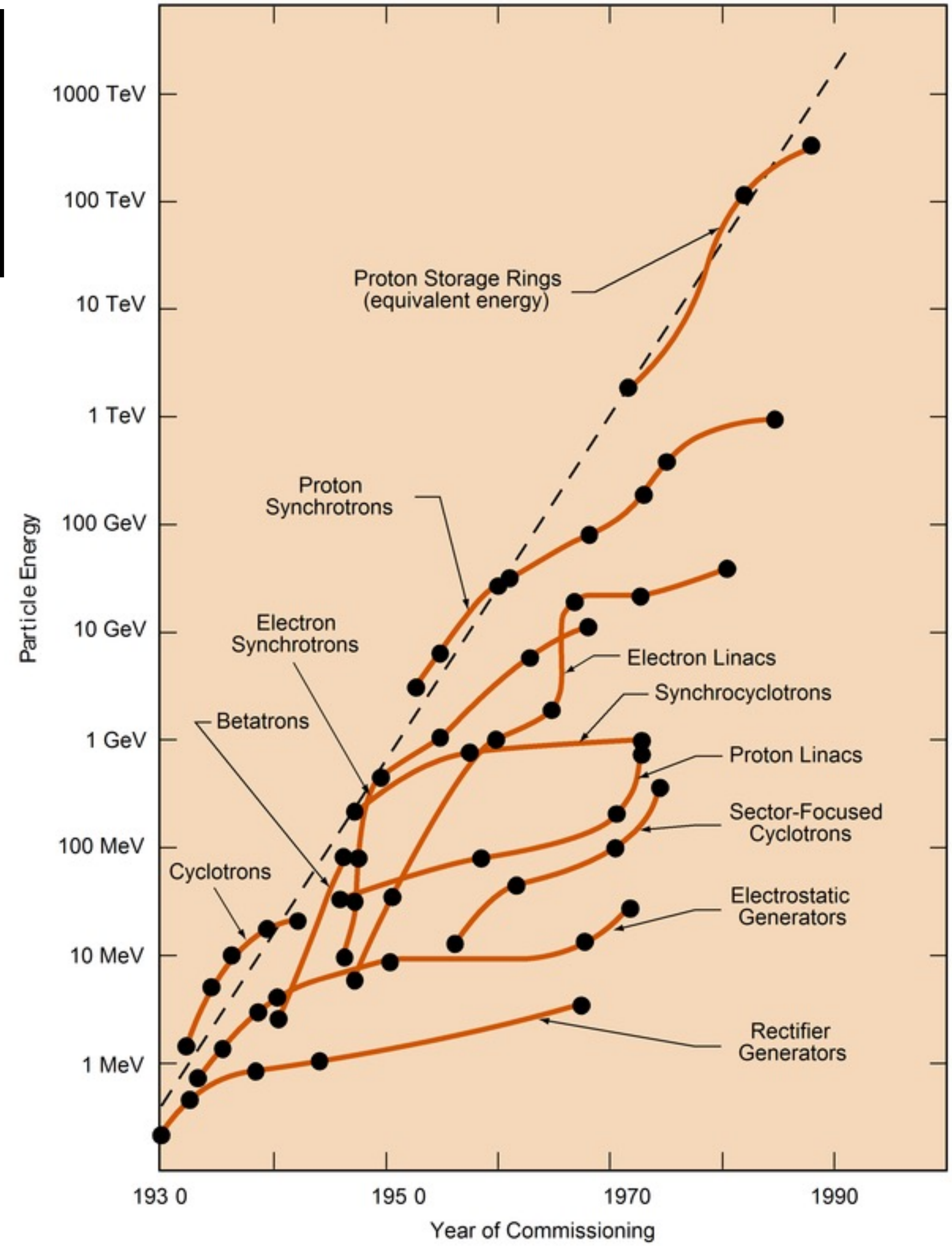
Accelerators

	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^-	$100 + 100$
$\mathrm{S}p\bar{p}\mathrm{S}$	CERN	$p\bar{p}$	$310 + 310$
Tevatron I	Fermilab	$p\bar{p}$	$1000 + 1000$
HERA	Hamburg	ep	$30e + 820p$
LHC (2005)[a]	CERN	pp	$7000 + 7000$

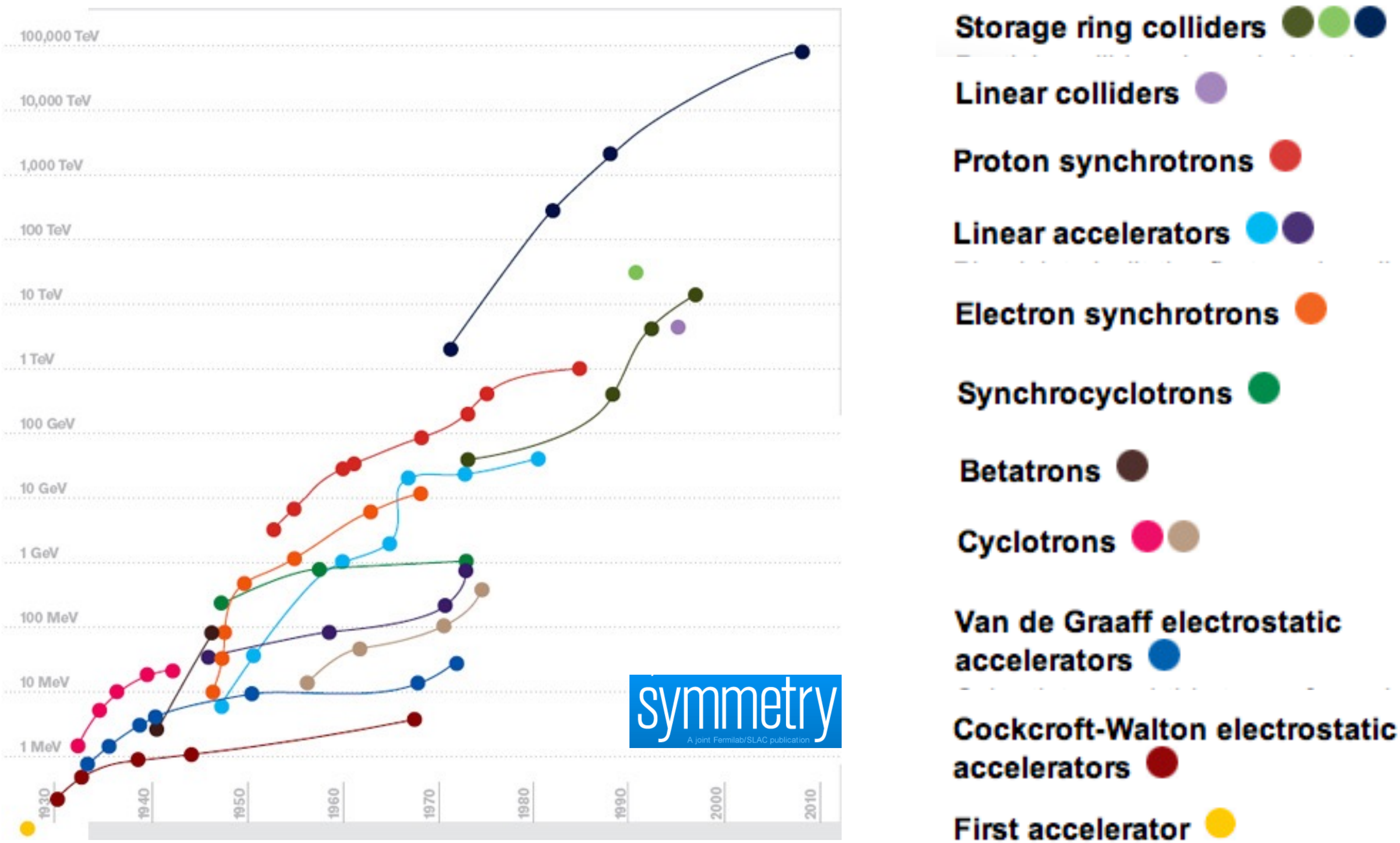
[a] Expected completion date

Historical Development

- Livingston Plot
  - updated by Panofsky



Historical Development



Fixed Target and Colliding Beam Accelerators

- Early experiments were done with a beam of particles and a fixed target
  - The energy in the center-of-mass is

    $s \equiv E_{cm}^2 = (E_{beam} + m_{target})^2 - p_{beam}^2$

    $= 2\, E_{beam}\, m_{target} + m_{target}^2 + m_{beam}^2 \sim 2\, E_{beam}\, m_{target}$
  - E_{cm} only increases as the square root of E_{beam}

    (note $\sqrt{s} \equiv E_{cm}$)

- By colliding beams of particles, E_{cm} increases linearly with E_{beam}

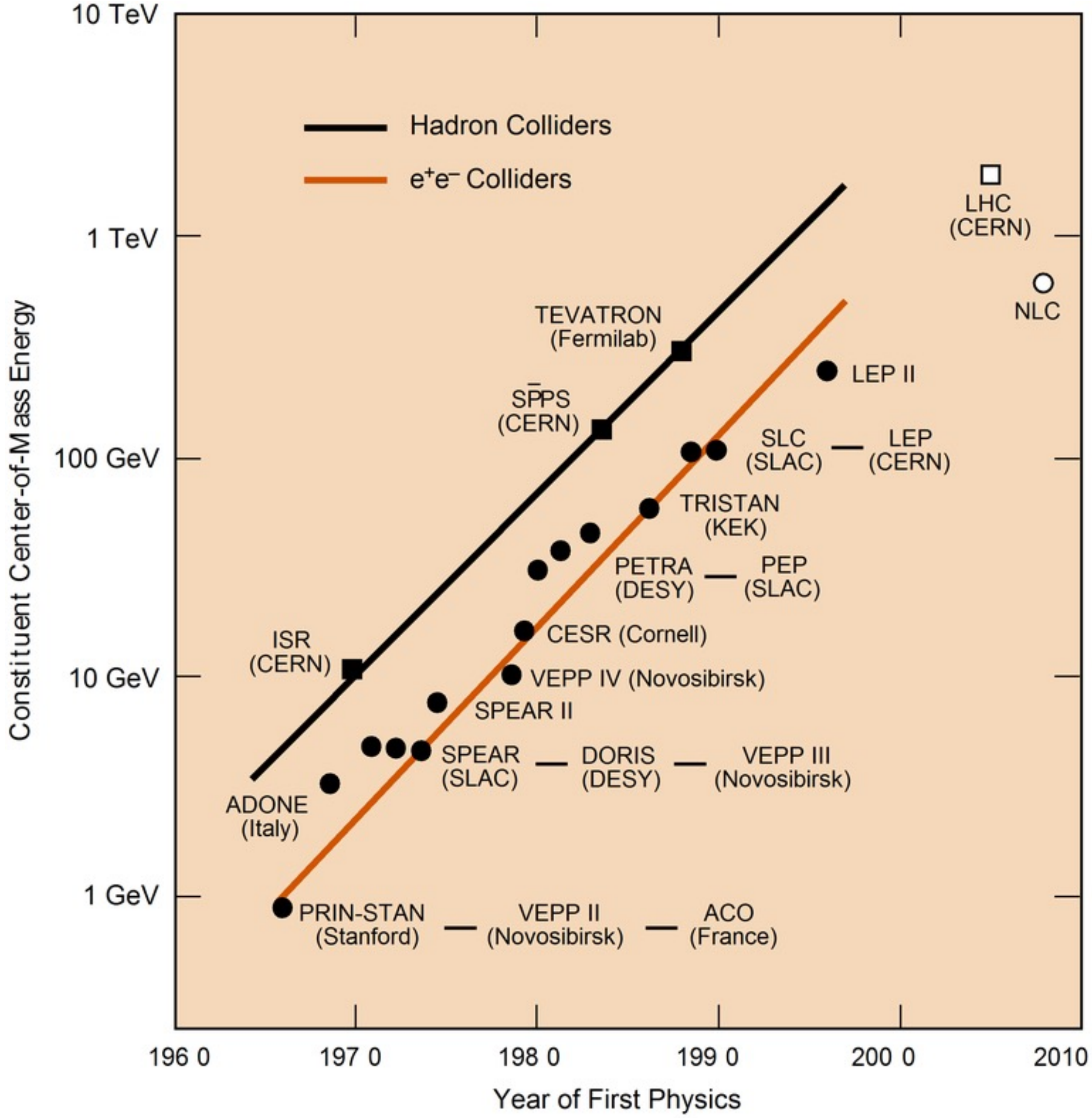
  $s \equiv E_{cm}^2 = (E_{beam} + E_{beam})^2 - (p_{beam} - p_{beam})^2$

  $= 4\, E_{beam}^2$

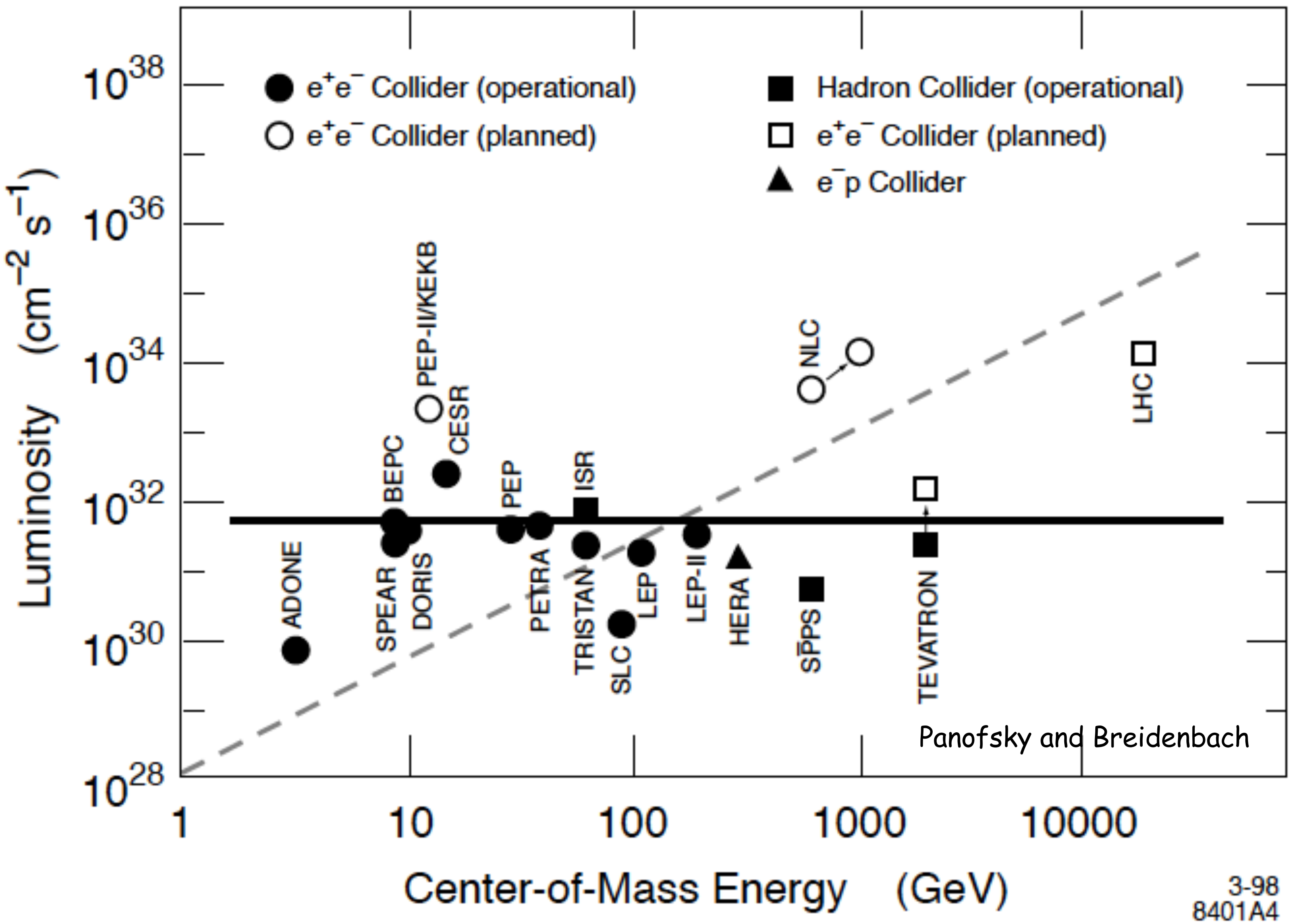
- The relationship between the two cases, to achieve the same s

  $E_{bm}^{FT} = 2\, (E_{bm}^{CB})^2 / m$

Historical Development



Historical Development



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

Updated in early 2010 with numbers received from representatives of the colliders (contact J. Beringer, LBNL). For existing (future) colliders the latest achieved (design) values are given. Quantities are, where appropriate, r.m.s.; H and V indicate horizontal and vertical directions; s.c. stands for superconducting. Parameters for the defunct SPEAR, DORIS, PETRA, PEP, SLC, 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	2008	1994	1989	2008	1999
Physics end date	—	—	2005	—	2013
Maximum beam energy (GeV)	1.0	6	2.2	1.89 (2.3 max)	0.700
Luminosity (10^{30} cm^{-2}s^{-1})	100	20	12.6 at 1.843 GeV/beam 5 at 1.55 GeV/beam	330	450 (1000 achievable)
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	1.3	low current: 1 high current: 2
Beam radius (10^{-6} m)	125 (round)	H: 1000 V: 30	H: 890 V: 37	H: 380 V: 5.7	H: 800 V: 4.8
Free space at interaction point (m)	±1	±2	±2.15	±0.63	±0.40
Luminosity lifetime (hr)	continuous	2	7–12	1.5	0.3
Turn-around time (min)	continuous	18	32	26	3
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: 0.52
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: 0.25 V: 0.009
Beam-beam tune shift per crossing (units 10^{-4})	H: 750 V: 750	500	350	200	250
RF frequency (MHz)	172	180	199.53	499.8	368

Particle Data Group

	VEPP-2000 (Novosibirsk)	VEPP-4M (Novosibirsk)	BEPC (China)	BEPC-II (China)	DAΦNE (Frascati)
Particles per bunch (units 10^{10})	16	15	20 at 2 GeV 11 at 1.55 GeV	3.6	e^-: 3.3 e^+: 2.4
Bunches per ring per species	1	2	1	93	120 (incl. 10 bunch gap)
Average beam current per species (mA)	150	80	40 at 2 GeV 22 at 1.55 GeV	580	e^-: 1800 e^+: 1300
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	1
Length of standard cell (m)	12	7.2	6.6	Outer ring: 6.6 Inner ring: 6.2	12
Phase advance per cell (deg)	H: 738 V: 378	65	$\approx$ 60	60–90 non-standard cells	360
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	1.7

Particle Data Group

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

Updated in early 2010 with numbers received from representatives of the colliders (contact J. Beringer, LBNL). For existing (future) colliders the latest achieved (design) values are given. Quantities are, where appropriate, r.m.s.; H and V indicate horizontal and vertical directions; s.c. stands for superconducting.

	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	ILC (TBD)
Physics start date	1979	2002	1989	TBD
Physics end date	2002	2008	2000	—
Maximum beam energy (GeV)	6	6	100 - 104.6	250 (upgradeable to 500)
Luminosity (10^{30} cm^{-2}s^{-1})	1280 at 5.3 GeV/beam	76 at 2.08 GeV/beam	24 at Z^0 100 at > 90 GeV	2×10^4
Time between collisions (μs)	0.014 to 0.22	0.014 to 0.22	22	$0.3^‡$
Full crossing angle (μ rad)	±2000	±3300	0	14000
Energy spread (units 10^{-3})	0.6 at 5.3 GeV/beam	0.82 at 2.08 GeV/beam	0.7→1.5	1
Bunch length (cm)	1.8	1.2	1.0	0.03
Beam radius (μm)	H: 460 V: 4	H: 340 V: 6.5	H: 200 → 300 V: 2.5 → 8	H: 0.639 V: 0.0057
Free space at interaction point (m)	±2.2 (±0.6 to REC quads)	±2.2 (±0.3 to PM quads)	±3.5	±3.5
Luminosity lifetime (hr)	2–3	2–3	20 at Z^0 10 at > 90 GeV	n/a
Turn-around time (min)	5 (topping up)	1.5 (topping up)	50	n/a
Injection energy (GeV)	1.8–6	1.5–6	22	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: 0.02 V: 8×10^{-5} (at 250 GeV)
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: 0.02 V: 0.0004
Beam-beam tune shift per crossing (units 10^{-4})	H: 250 V: 620	e^-: 420 (H), 280 (V) e^+: 410 (H), 270 (V)	830	n/a
RF frequency (MHz)	500	500	352.2	1300

Particle Data Group

	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	ILC (TBD)
Particles per bunch (units 10^{10})	1.15	4.7	45 in collision 60 in single beam	2
Bunches per ring per species	9 trains of 5 bunches	8 trains of 3 bunches	4 trains of 1 or 2	2625
Average beam current per species (mA)	340	72	4 at Z^0 4→6 at > 90 GeV	9 (in pulse)
Beam polarization (%)	—	—	55 at 45 GeV 5 at 61 GeV	e^-: > 80% e^+: > 60%
Circumference or length (km)	0.768	0.768	26.66	31
Interaction regions	1	1	4	1
Magnetic length of dipole (m)	1.6–6.6	1.6–6.6	11.66/pair	n/a
Length of standard cell (m)	16	16	79	n/a
Phase advance per cell (deg)	45–90 (no standard cell)	45–90 (no standard cell)	102/90	n/a
Dipoles in ring	86	84	3280+24 inj. + 64 weak	n/a
Quadrupoles in ring	101 + 4 s.c.	101 + 4 s.c.	520+288 + 8 s.c.	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	n/a

‡Time between bunch trains: 200ms.

Particle Data Group

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

Updated in early 2010 with numbers received from representatives of the colliders (contact J. Beringer, LBNL). For existing (future) colliders the latest achieved (design) values are given. Quantities are, where appropriate, r.m.s.; H and V indicate horizontal and vertical directions; s.c. stands for superconducting.

	KEKB (KEK)	PEP-II (SLAC)	SuperB (Italy)	SuperKEKB (KEK)
Physics start date	1999	1999	TBD	2014 ?
Physics end date	—	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) (nominal $E_{\rm cm}$ = 10.5 GeV)	e^-: 4.2 e^+: 6.7	e^-: 7 e^+: 4
Luminosity (10^{30} cm^{-2}s^{-1})	21083	12069 (design: 3000)	1.0×10^6	8×10^5
Time between collisions (μs)	0.00590 or 0.00786	0.0042	0.0042	0.004
Full crossing angle (μ rad)	$\pm11000^\dagger$	0	±33000	±41500
Energy spread (units 10^{-3})	0.7	e^-/e^+: 0.61/0.77	e^-/e^+: 0.73/0.64	e^-/e^+: 0.58/0.84
Bunch length (cm)	0.65	e^-/e^+: 1.1/1.0	0.5	e^-/e^+: 0.5/0.6
Beam radius (μm)	H: 124 (e^-), 117 (e^+) V: 0.94	H: 157 V: 4.7	H: 8 V: 0.04	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	±0.35	$e^-: +1.20/-1.28, e^+: +0.78/-0.73$ ($+300/-500$) mrad cone
Luminosity lifetime (hr)	continuous	continuous	continuous	continuous
Turn-around time (min)	continuous	continuous	continuous	continuous
Injection energy (GeV)	e^-/e^+: 8/3.5	2.5–12	e^-/e^+ : 4.2/6.7	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), 1.5 (V) e^+: 24 (H), 1.5 (V)	e^-: 2.5 (H), 0.006 (V) e^+: 2.0 (H), 0.005 (V)	5 (H), 3 (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^-: 0.032 (H), 0.00021 (V) e^+: 0.026 (H), 0.00025 (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)	20 (H), 950 (V)	e^-: 12 (H), 807 (V) e^+: 28 (H), 893 (V)
RF frequency (MHz)	508.887	476	476	508.887

Particle Data Group

	KEKB (KEK)	PEP-II (SLAC)	SuperB (Italy)	SuperKEKB (KEK)
Particles per bunch (units 10^{10})	e^-/e^+: 4.7/6.4	e^-/e^+: 5.2/8.0	e^-/e^+: 5.1/6.5	e^-/e^+: 6.53/9.04
Bunches per ring per species	1585	1732	978	2500
Average beam current per species (mA)	e^-/e^+: 1188/1637	e^-/e^+: 1960/3026	e^-/e^+: 1900/2400	e^-/e^+: 2600/3600
Beam polarization (%)	—	—	> 80	—
Circumference or length (km)	3.016	2.2	1.258	3.016
Interaction regions	1	1	1	1
Magnetic length of dipole (m)	e^-/e^+ : 5.86/0.915	e^-/e^+: 5.4/0.45	e^-/e^+: 0.9/5.4	e^-/e^+ : 5.9/4.0
Length of standard cell (m)	e^-/e^+ : 75.7/76.1	15.2	40	e^-/e^+ : 75.7/76.1
Phase advance per cell (deg)	450	e^-/e^+: 60/90	360 (V), 1080 (H)	450
Dipoles in ring	e^-/e^+ : 116/112	e^-/e^+: 192/192	e^-/e^+: 186/102	e^-/e^+ : 116/112
Quadrupoles in ring	e^-/e^+ : 452/452	e^-/e^+: 290/326	e^-/e^+: 290/300	e^-/e^+ : 466/460
Peak magnetic field (T)	e^-/e^+ : 0.25/0.72	e^-/e^+: 0.18/0.75	e^-/e^+: 0.52/0.25	e^-/e^+ : 0.22/0.19

†KEKB is operating with crab crossing since February 2007.

*With dynamic beam-beam effect.

Particle Data Group

HIGH-ENERGY COLLIDER PARAMETERS: ep, $\bar{p}p$, pp, and Heavy Ion Colliders

Updated in early 2010 with numbers received from representatives of the colliders (contact J. Beringer, LBNL). For existing (future) colliders the latest achieved (design) values are given. Quantities are, where appropriate, r.m.s.; H and V indicate horizontal and vertical directions; s.c. stands for superconducting; pk and ave denote peak and average values.

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)				LHC† (CERN)	
Physics start date	1992	1987	2001	2000	2004	2002	2009	2010
Physics end date	2007	—	—				—	
Particles collided	ep	$p\bar{p}$	pp (pol.)	Au Au	Cu Cu	d Au	pp	Pb Pb
Maximum beam energy (TeV)	e: 0.030 p: 0.92	0.980	0.25 34% pol	0.1 TeV/n	0.1 TeV/n	0.1 TeV/n	7.0 (3.5)	2.76 TeV/n (1.38 TeV/n)
Luminosity (10^{30} cm^{-2}s^{-1})	75	402	85 (pk) 55 (ave)	0.0040 (pk) 0.0020 (ave)	0.020 (pk) 0.0008 (ave)	0.27 (pk) 0.14 (ave)	1.0×10^4 (170)	1.0×10^{-3} (1.3×10^{-5})
Time between collisions (ns)	96	396	107	107	321	107	24.95 (49.90)	99.8 (1347)
Full crossing angle (μ rad)	0	0	0				≈ 300	≤ 100 (0)
Energy spread (units 10^{-3})	e: 0.91 p: 0.2	0.14	0.15	0.75	0.75	0.75	0.113 (0.116)	0.11
Bunch length (cm)	e: 0.83 p: 8.5	p: 50 $\bar{p}$: 45	55	30	30	30	7.55 (5.87)	7.94 (5.83)
Beam radius (10^{-6} m)	e: $280(H), 50(V)$ p: $265(H), 50(V)$	p: 28 $\bar{p}$: 16	90	135	145	145	16.6 (45)	15.9 (45)
Free space at interaction point (m)	±2	±6.5	16				38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	10	6 (average)	2.0	1.1	1.8	1.5	14.9 (8)	10.9 - 3.6‡ (150 - 50)‡
Turn-around time (min)	e: 75, p: 135	90	200	100	145	145	≈ 180	
Injection energy (TeV)	e: 0.012 p: 0.040	0.15	0.023	0.011 TeV/n	0.011 TeV/n	0.012 TeV/n	0.450	0.177 TeV/n
Transverse emittance ($10^{-9}\pi$ rad-m)	e: $20(H), 3.5(V)$ p: $5(H), 5(V)$	p: 3 $\bar{p}$: 1	11	25	23	25	0.5 (1.0)	0.5 (1.0)
β^*, ampl. function at interaction point (m)	e: $0.6(H), 0.26(V)$ p: $2.45(H), 0.18(V)$	0.28	0.7	0.75	0.9	0.85	0.55 (2.0)	0.5 (2.0)
Beam-beam tune shift per crossing (units 10^{-4})	e: $190(H), 450(V)$ p: $12(H), 9(V)$	p: 120 $\bar{p}$: 120	47	16	30	d: 21 Au: 17	34 (23)	—
RF frequency (MHz)	e: 499.7 p: 208.2/52.05	53	accel: 28 store: 28	accel: 28 store: 197	accel: 28 store: 197	accel: 28 store: 197	400.8	400.8

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC (Brookhaven)				LHC† (CERN)	
Particles per bunch (units 10^{10})	e: 3 p: 7	p: 26 $\bar{p}$: 9	11	0.12	0.45	d: 10 Au: 0.1	11.5 (7)	0.007
Bunches per ring per species	e: 189 p: 180	36	111	111	37	95	2808 (796)	592 (62)
Average beam current per species (mA)	e: 40 p: 90	p: 70 $\bar{p}$: 24	152	127	60	d: 119 Au: 94	584 (100)	6.12 (0.641)
Circumference (km)	6.336	6.28	3.834				26.659	
Interaction regions	2 colliding beams 1 fixed target (e beam)	2 high $\mathcal{L}$	6 total, 2 high $\mathcal{L}$				2 high $\mathcal{L}$ +2	1 dedicated +2
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	93	84	d: 84 Au: 93	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: $\bar{p}$ source accum. rate: 25×10^{10} hr^{-1}; max. no. of $\bar{p}$ stored: 3.1×10^{12} (Accumulator), 5.4×10^{12} (Recycler).
†Numbers in parentheses refer to goals for operation in 2010.
‡For 1 - 3 experiments.

Particle Data Group

Accelerators

- History
- Two Principles
  - Electrostatic
    - Cockcroft-Walton, Van de Graaff and tandem Van de Graaff
  - Transformers
    - Linear Induction, Cyclotron, Synchrocyclotron & Betatron
- Phase Stability
- Synchrotron
- Strong focusing
- Longitudinal stability (synchrotron oscillations)
- Strong focusing (alternating quadrupoles)
- Betatron oscillations (transverse oscillations) & Instabilities
- High-impedence Microwave Devices
- Superconducting Technology
- Luminosity lifetime

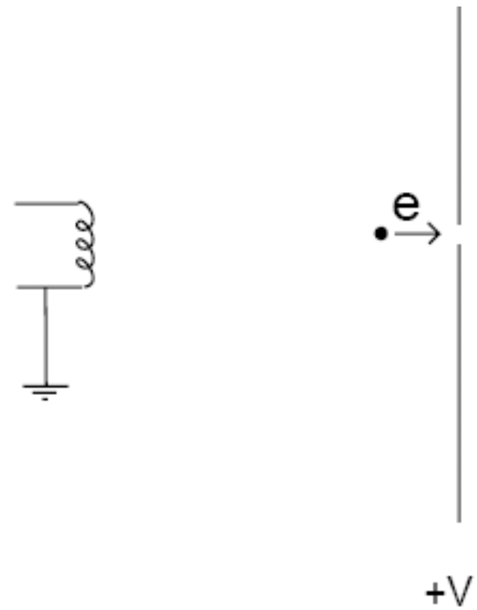
References:
Donald H. Perkins, Introduction to High Energy Physics, Fourth Edition
E.J.N.Wilson, "Physics of Accelerators"
M. Sands, SLAC-121, 1970
ACCELERATOR PHYSICS OF COLLIDERS - Revised August 2001
by K. Desler and D.A. Edwards (DESY), Particle

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 x 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

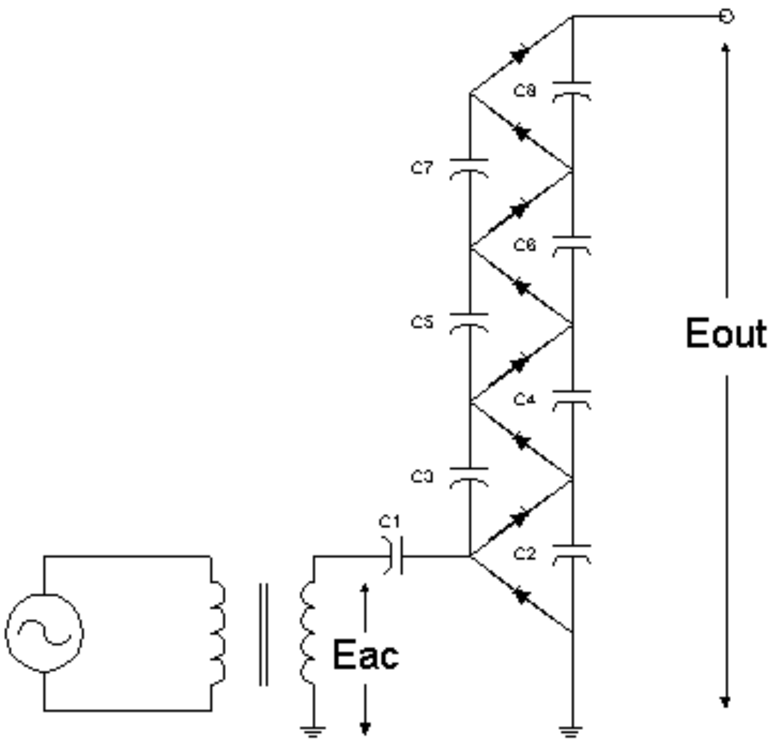
- The limitation of the electrostatic approach comes from the ultimate breakdown of high voltages

  - 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

Electrostatic

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



first stage of Fermilab complex is Cockroft-Walton

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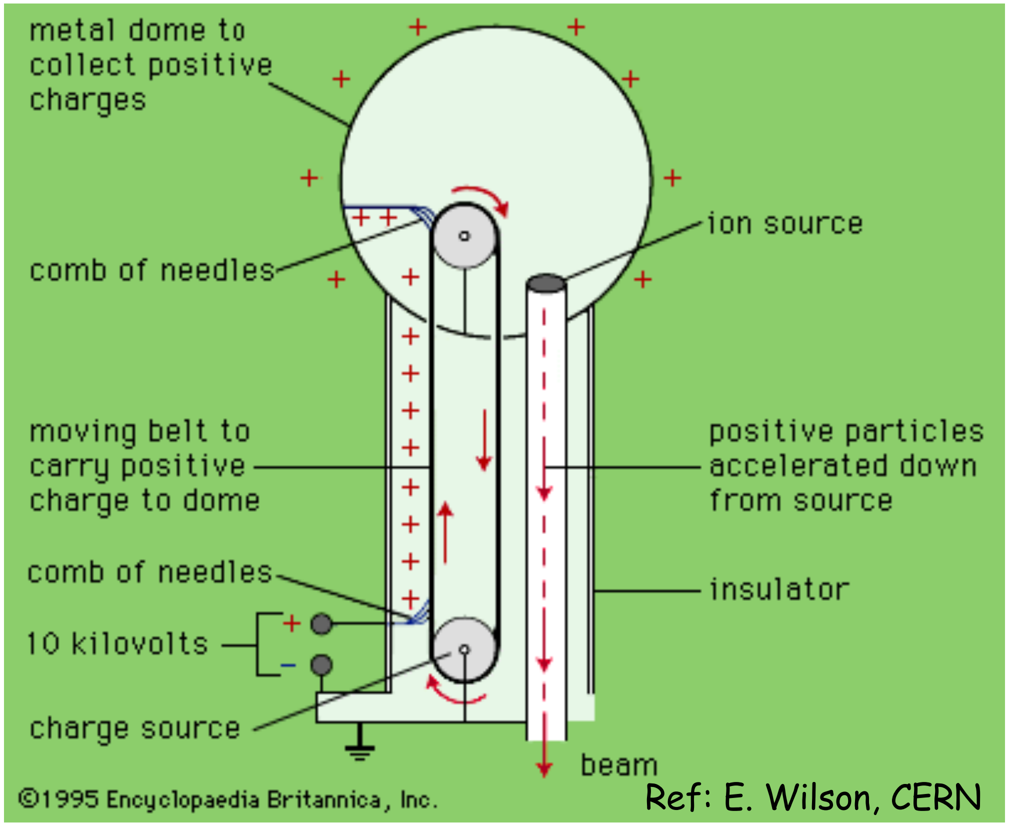
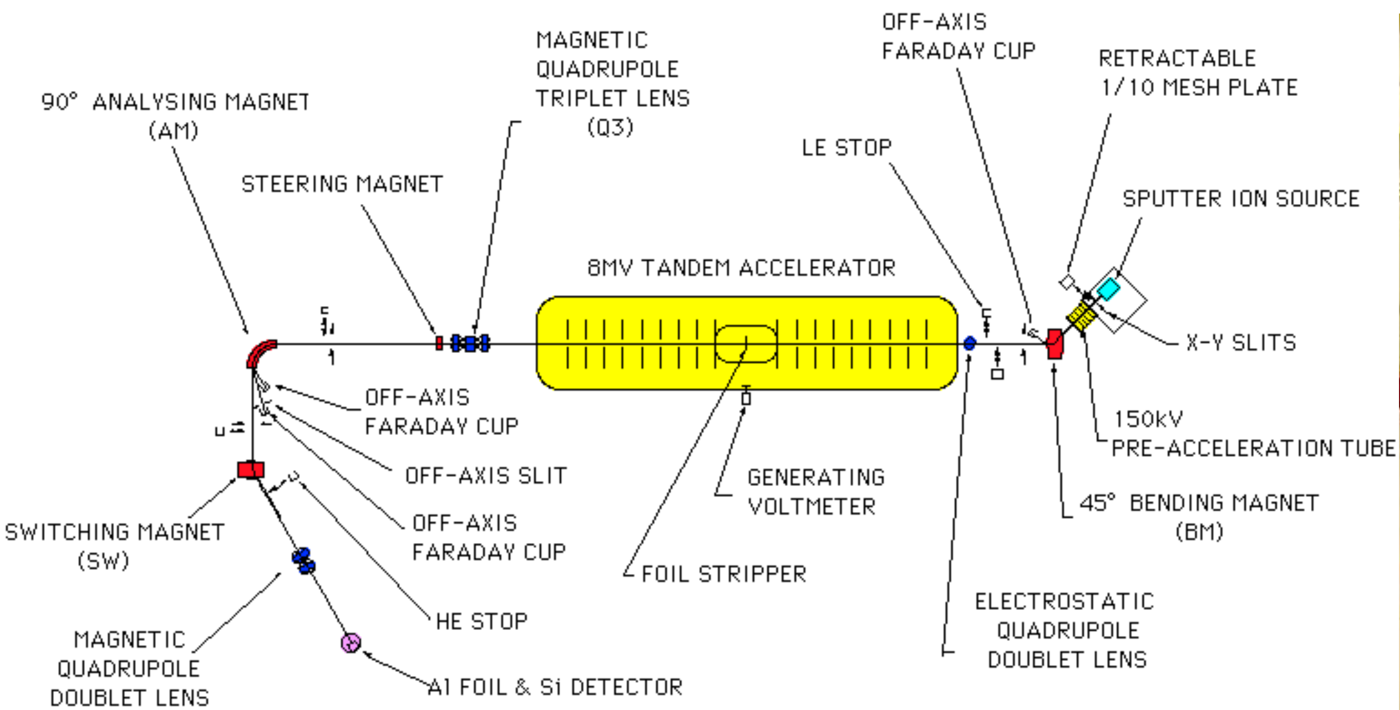
Electrostatic

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



Tandem Van de Graaff

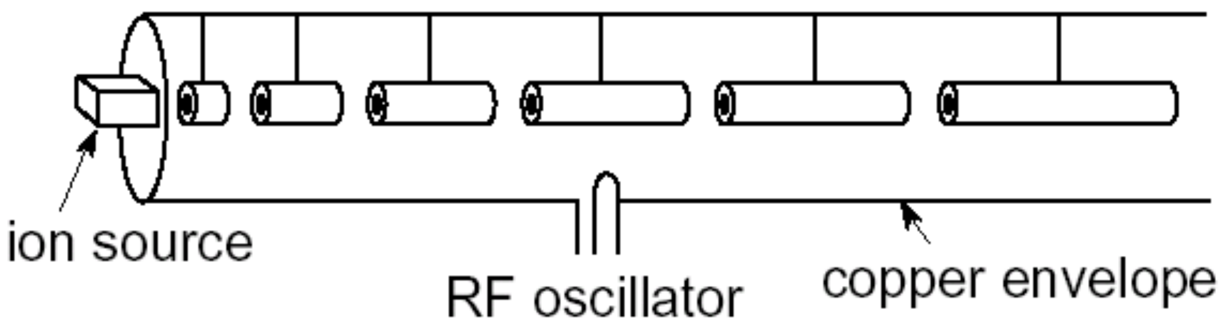
- Introduced in the 50's
  - accelerate negative ions, strip, and accelerate positive ions



Transformer

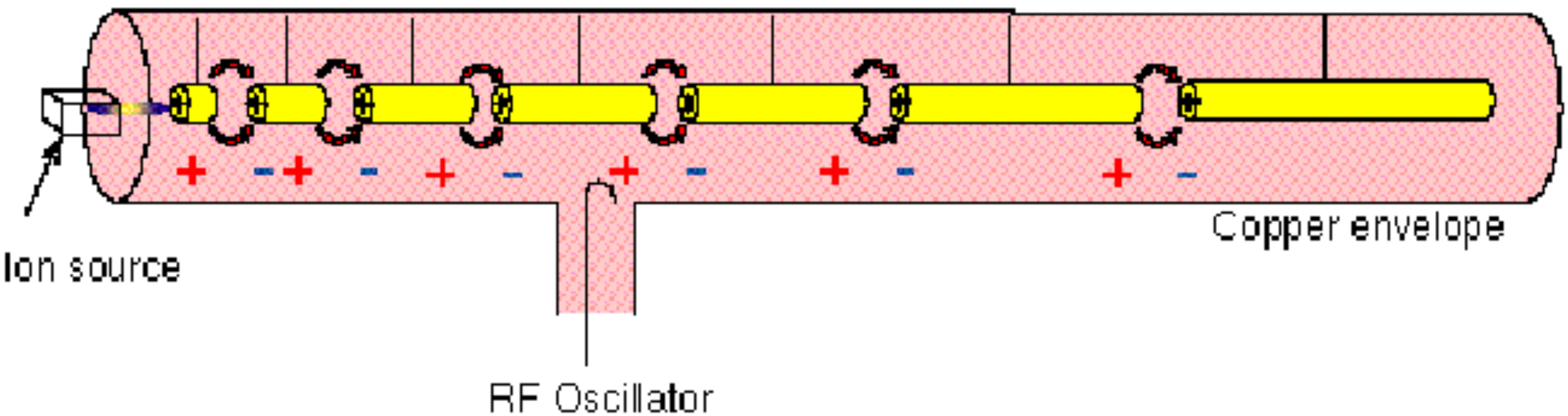
- Electrostatic approaches fail above tens of MeV – failure to generate large voltages
- Linear Accelerator
- Cyclotron
  - orbital period of nonrelativistic particles circulating in a uniform magnetic field is independent of energy
- Betatron
  - electrons become relativistic at moderate energies, and cyclotron fails

RF Linear Accelerator



- The early accelerators inspired the linear accelerator, where adding stages can increase energy reach
- Copper lined tubes in which oscillating fields are excited by radio transmitter ("drift tubes")
- But in order to increase beam energy, length must be expanded
- Circular accelerators were invented to make higher energy possible in a more compact device

RF Linear Accelerator



Ref: E. Wilson, CERN

Cyclotron

- Orbital period of nonrelativistic particles circulating in a uniform magnetic field is independent of energy

  $2\pi f = qB / m \approx 10^8$ B(Tesla) for deuterons

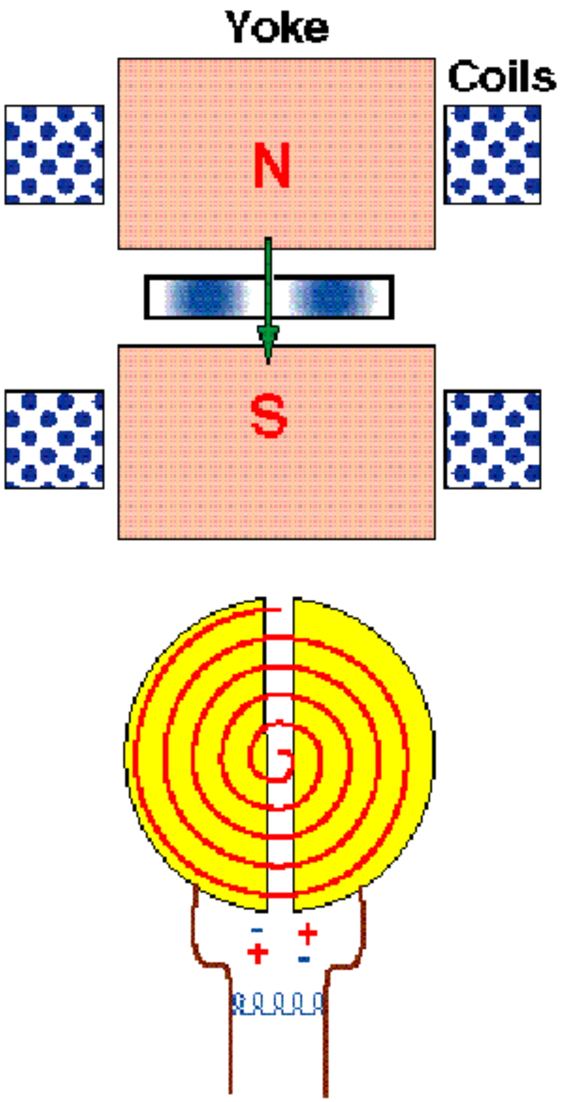
  radio frequency

- Match the revolution frequency with a RF voltage across a gap

- Focussing by small radial decrease in magnetic field
  - results in decrease in orbital frequency

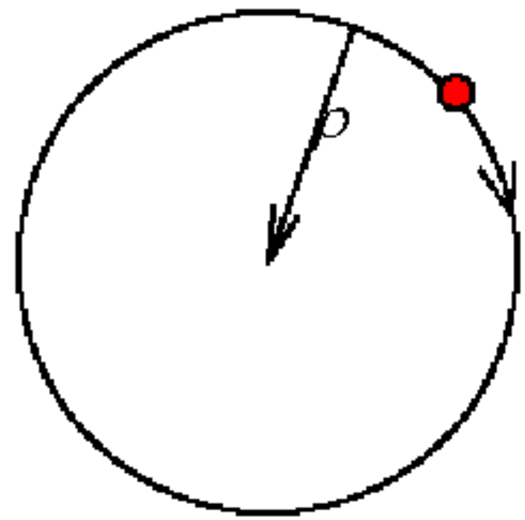
- 184-inch cyclotron at Berkeley for deuteron energies above 100 MeV

Cyclotron



$$e\mathbf{v}\times\mathbf{B}=\frac{mv^2}{\rho}$$

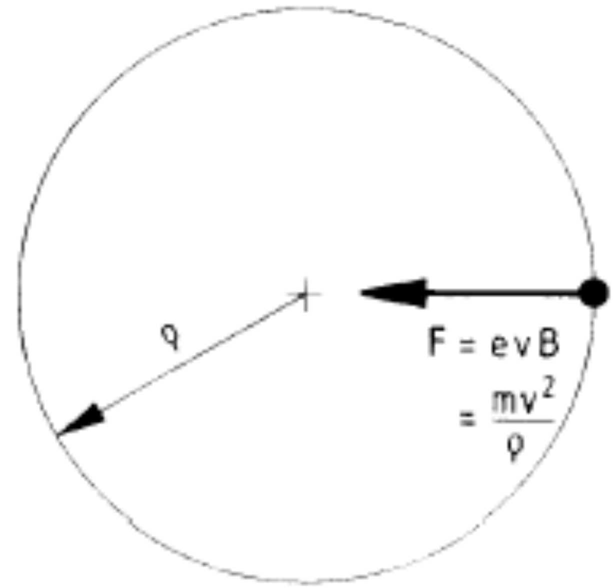
$$B\rho=\frac{mv}{e}=\frac{p}{e}$$



Ref: E. Wilson, CERN

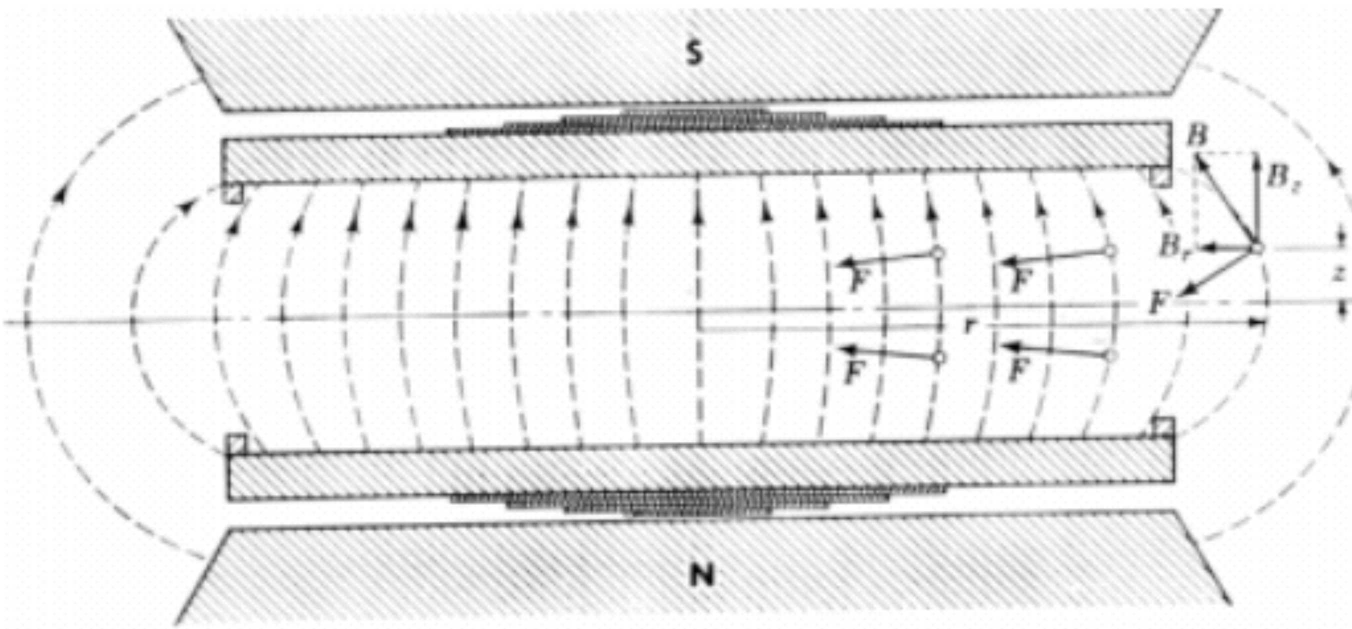
Cyclotron

- Nonrelativistic acceleration
- Particles spiral out in uniform magnetic field, B
- Balance of forces makes radius proportional to the velocity
  $\rho = \mathbf{v}\ (\mathbf{m/eB})$
- This means the period of rotation, $P = 2\pi\rho / v$, is a constant $= 2\pi\ m/eB$
- Focusing of orbits is needed to achieve the best currents
- Shims do this (see next page)
- The constancy of period breaks down for kinetic energies of about 5% mc^2



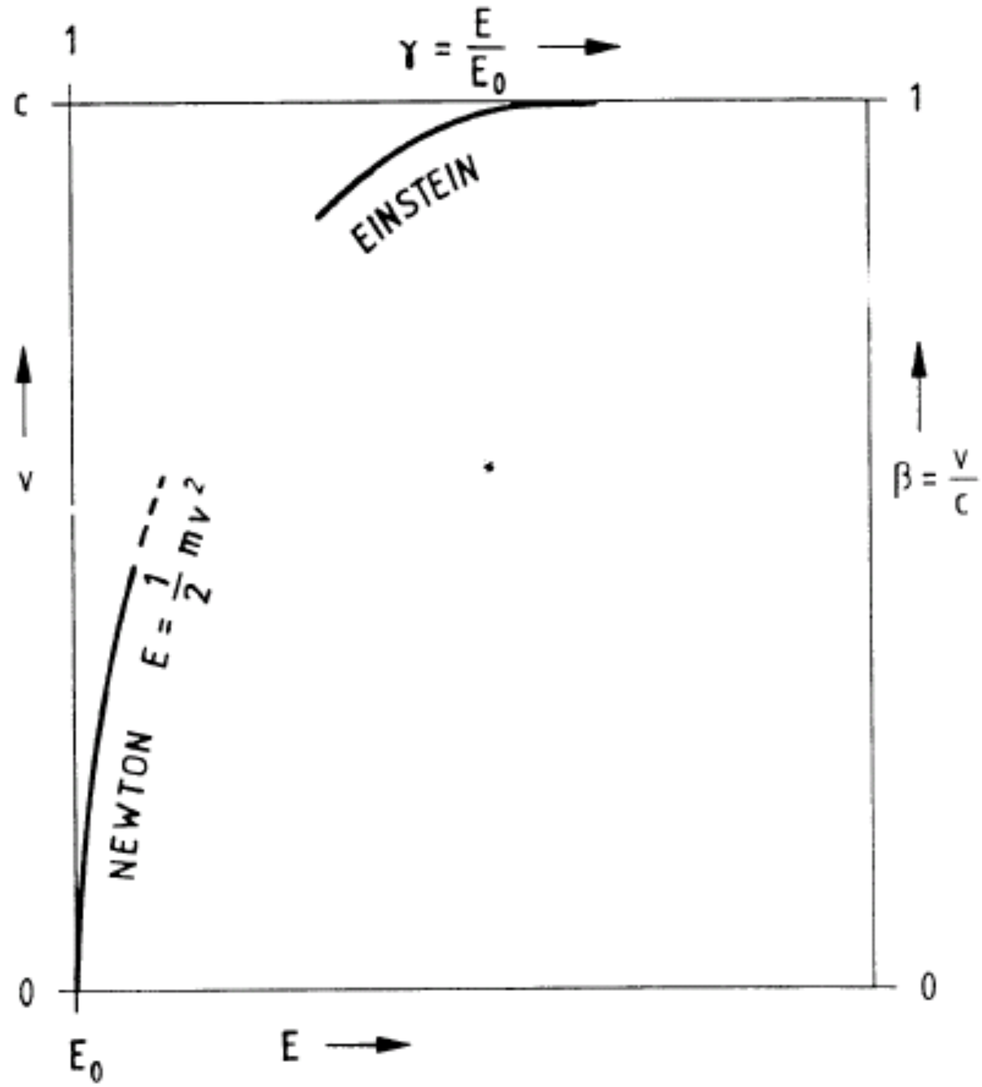
Cyclotron Focussing

- Shims lead to increased focussing
  - both vertical and horizontal
  - discovered more intense fields



Relativistic effect

Increase of velocity with energy

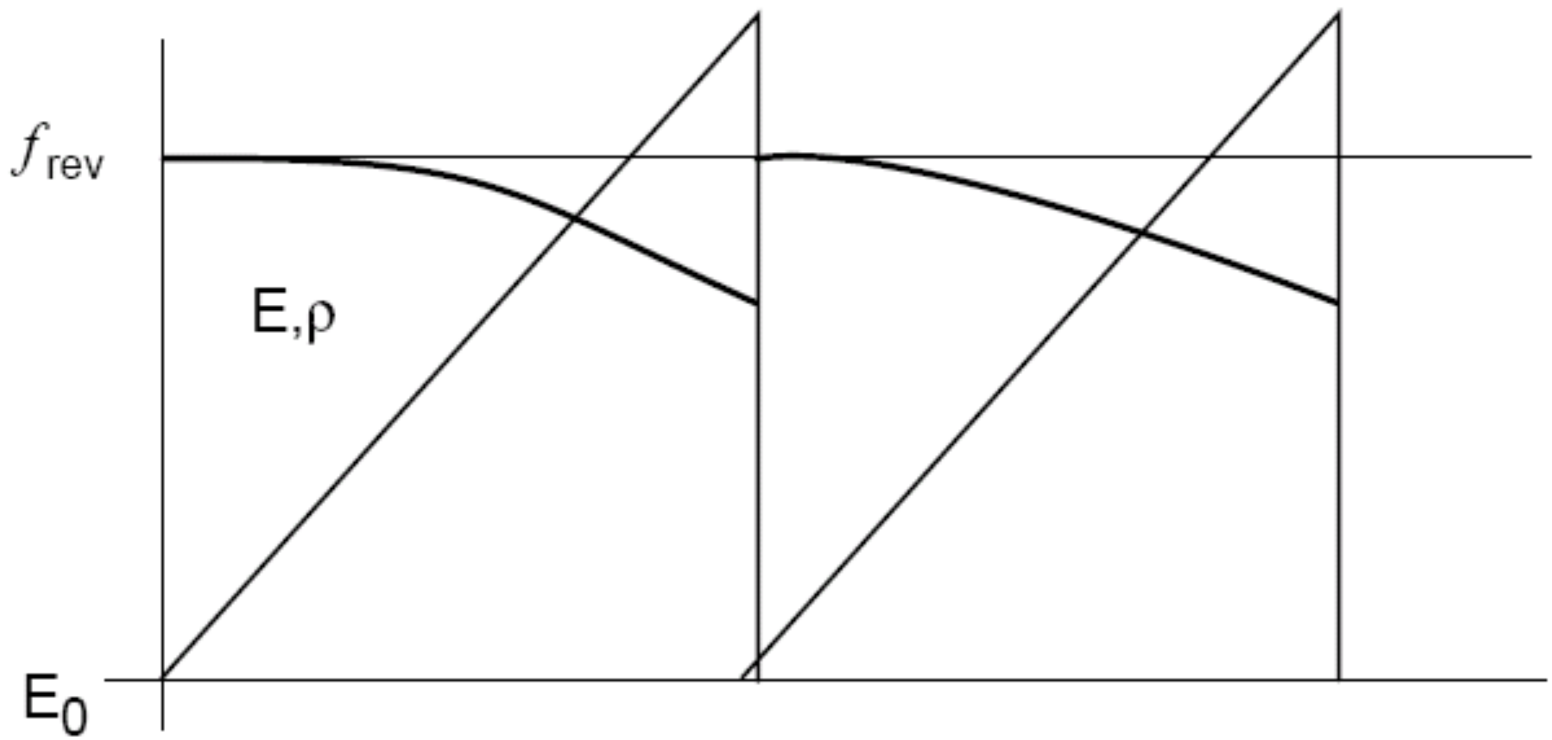


Synchrocyclotron

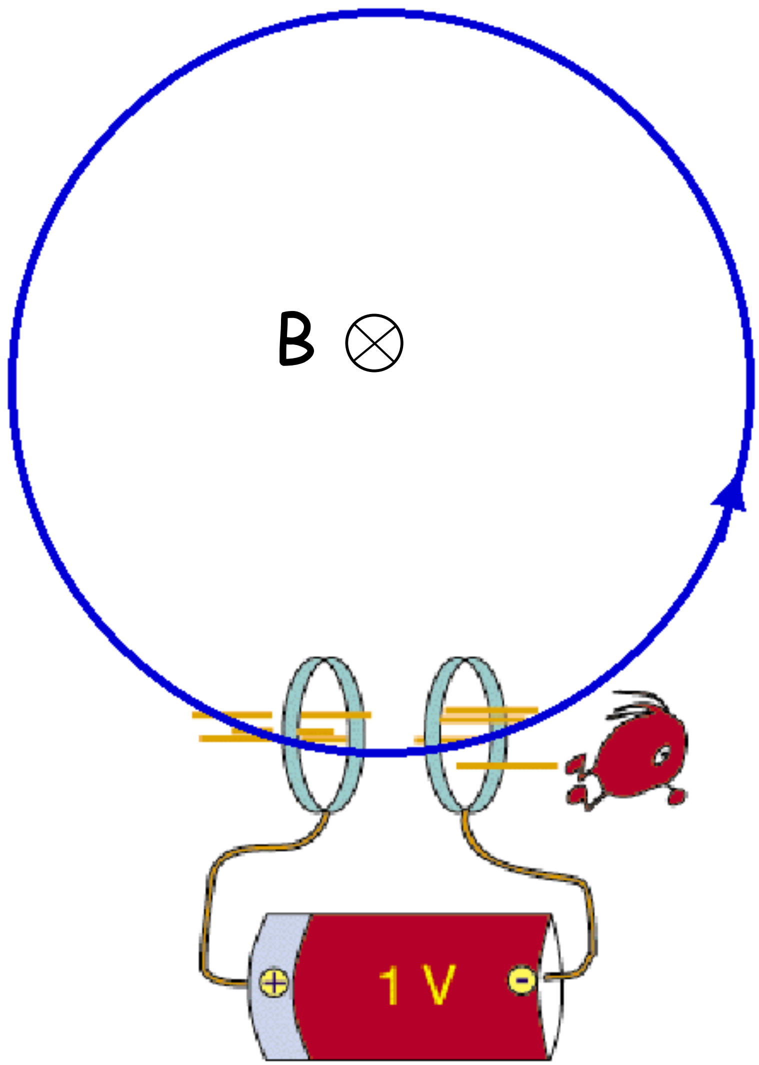
- Electrons become relativistic at moderate energies, and the cyclotron concept fails (period no longer constant)
- Problem: how to overcome the changing orbital period
- One solution: add radial magnetic field gradient
  - new problem: destroys vertical focusing
- Second solution: change the RF frequency as particles circulate
  - Okay – but an added problem: particles must now be accelerated in bursts, not continuously
- Synchrocylcotron
  - Static magnetic field
  - RF frequency decreases to match the revolution frequency as function of energy

Synchrocyclotron

The variation of revolution and RF frequencies as a function of time in a synchro-cyclotron



Simple Circular Accelerator



- Circular orbits determined by magnetic field
- Acceleration on each revolution

- Will this work?

Ref: E. Wilson, CERN

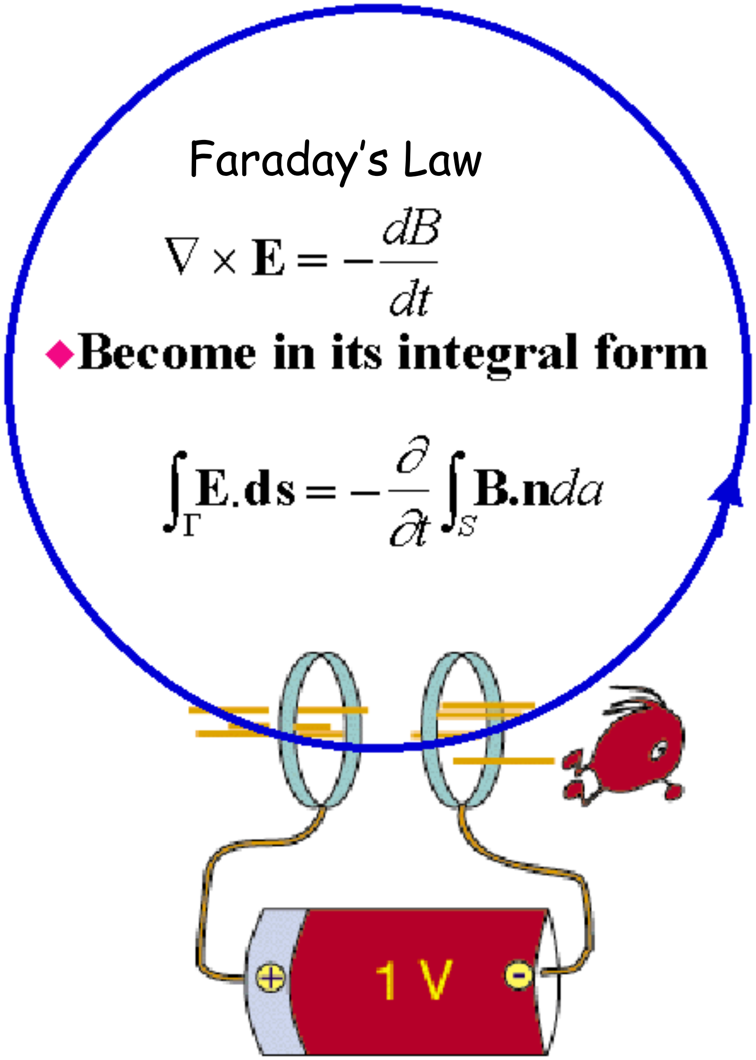
Simple Circular Accelerator

Faraday's Law

$$\nabla \times \mathbf{E} = -\frac{dB}{dt}$$

- **Become in its integral form**

$$\int_{\Gamma} \mathbf{E.ds} = -\frac{\partial}{\partial t}\int_{S} \mathbf{B.n}\,da$$



- There can be no acceleration without time dependent magnetic field
- The converse: time-dependent flux may accelerate particles

Ref: E. Wilson, CERN

Betatron

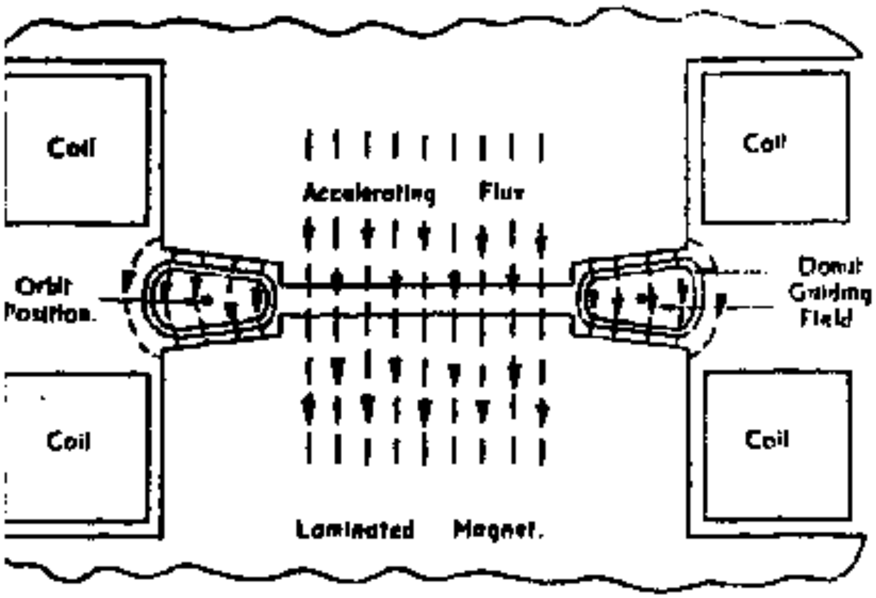
- Another concept to deal with the fact that the electrons become relativistic at moderate energies, and the cyclotron concept fails   (period no longer constant)

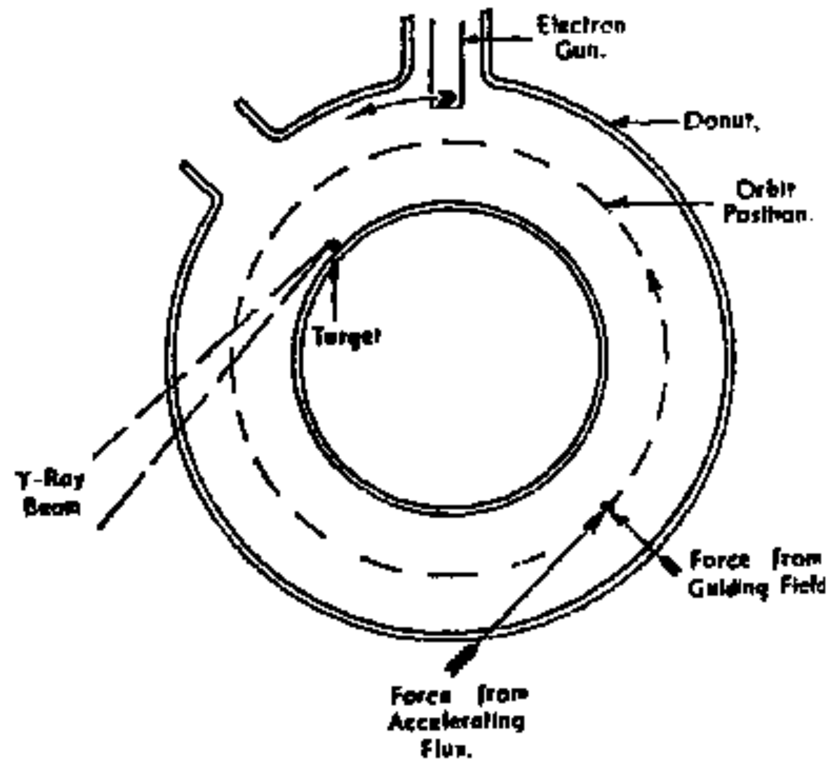
- Energy of electrons in circular orbit increased by the induced E field from an increasing flux in a central iron core

- Particles are kept in single circular orbit (not spirally out as in cyclotron)

- Limited at 300 MeV due to radiation losses which cannot be compensated

Betatron



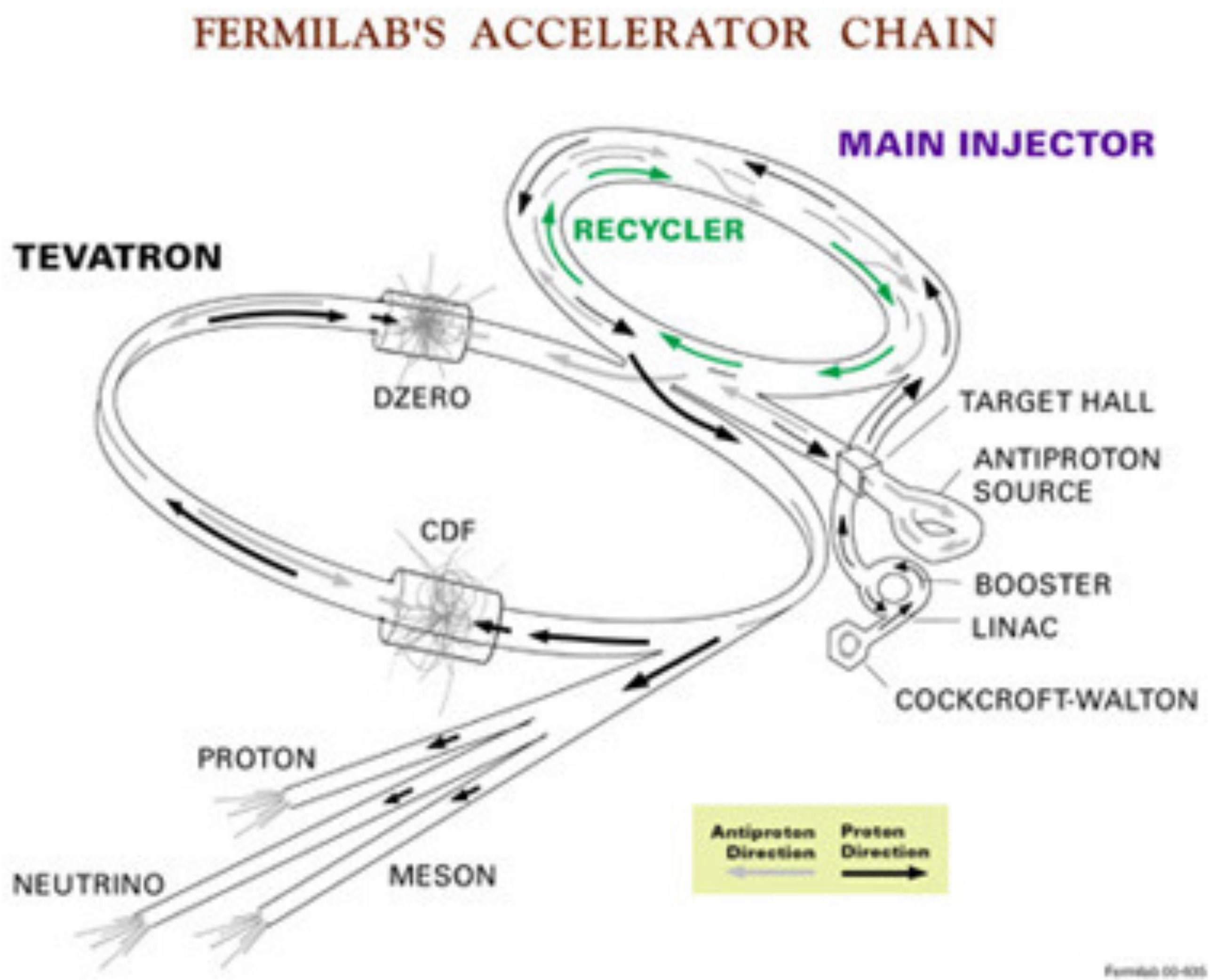


$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$$

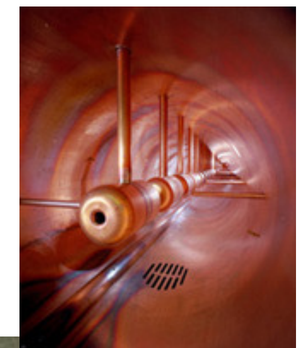
Ref: E. Wilson, CERN

Fermilab's chain of accelerators

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



Fermilab' s chain of accelerators



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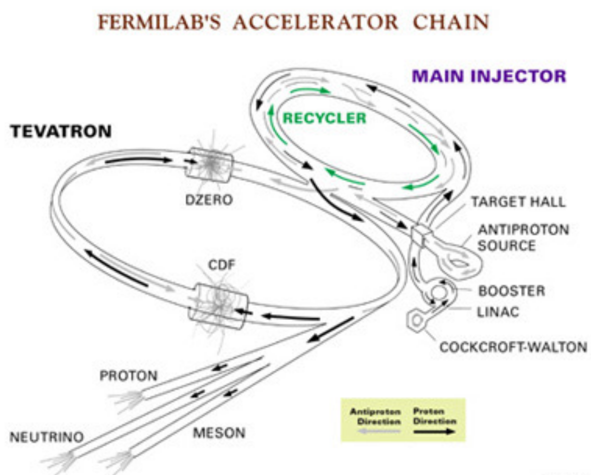
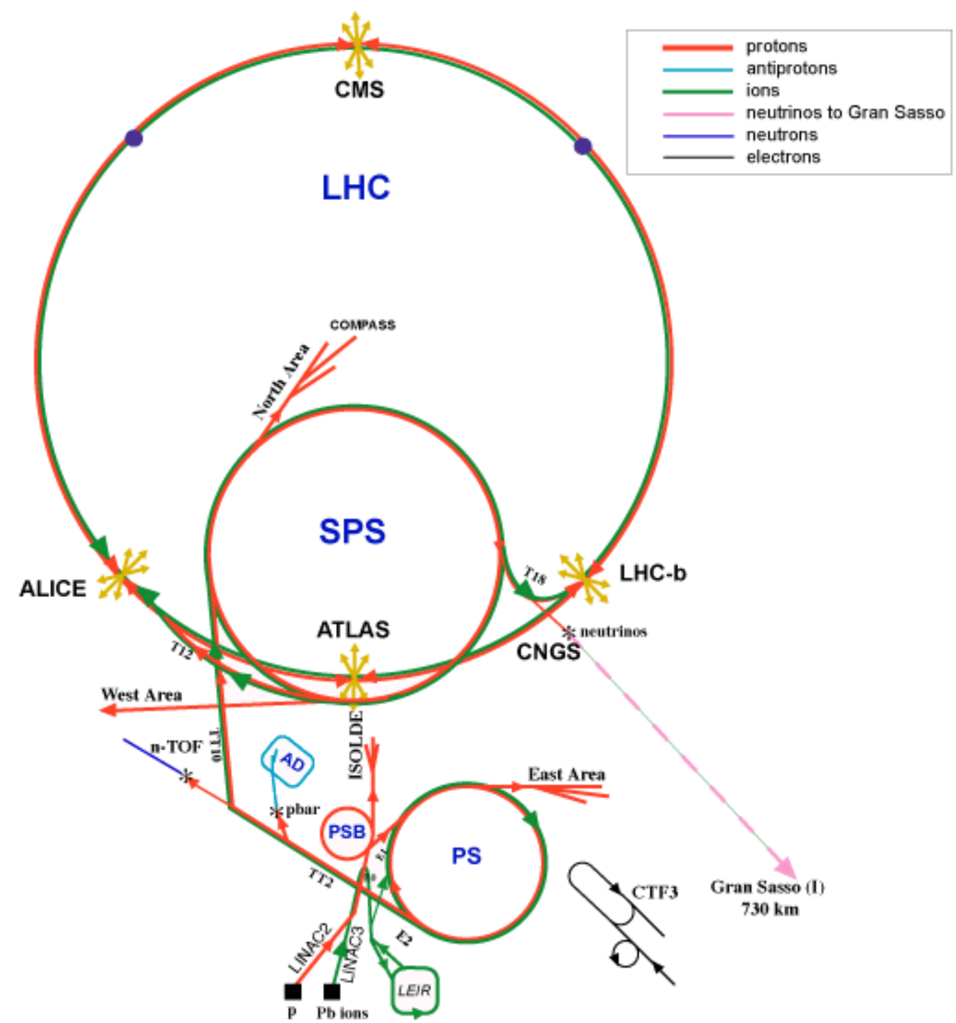


LHC Complex

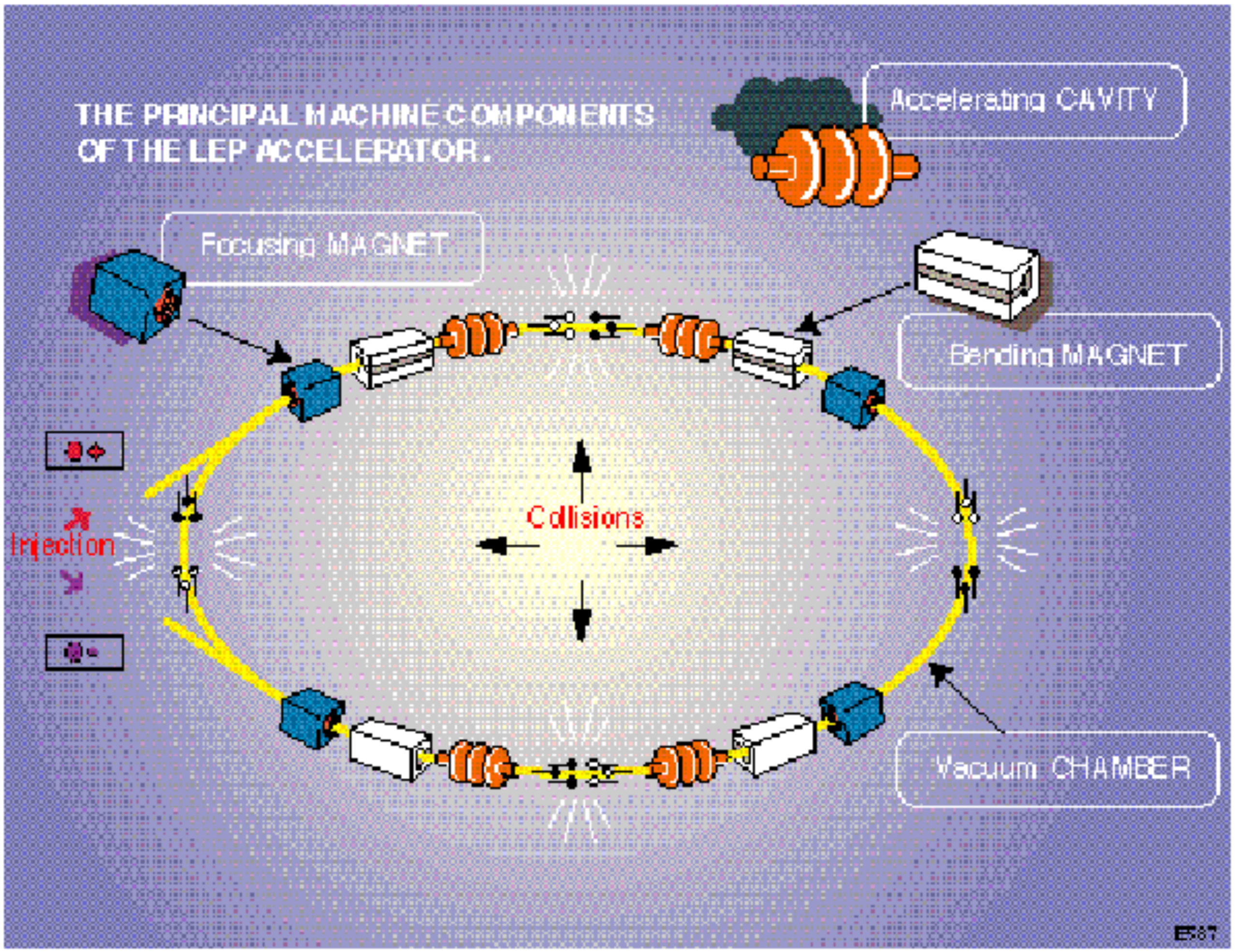
1) Protons extracted from hydrogen
2) LINAC2 accelerates to 50 MeV
3) PSB boosts to 1.4 GeV
4) PS accelerates to 25 GeV
5) SPS accelerates to 450 GeV
6) 7000 GeV (7 TeV) in the LHC

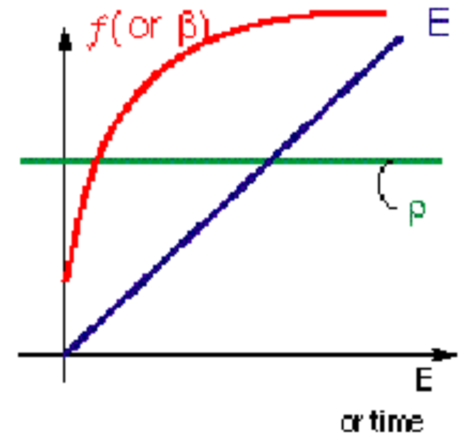
CERN Accelerators
(not to scale)

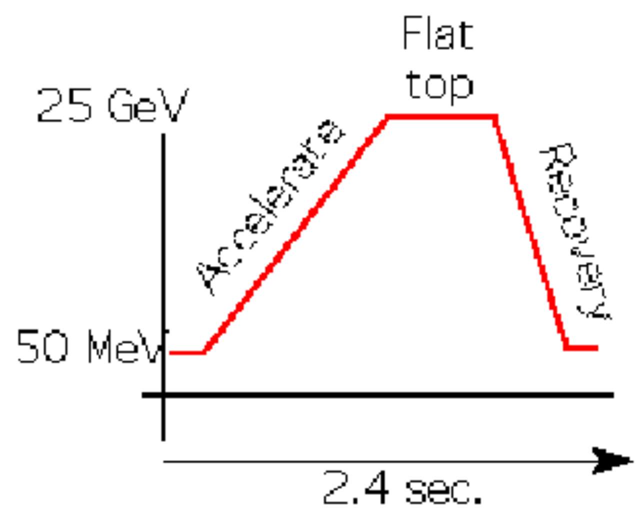


LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Seperator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Synchrotron







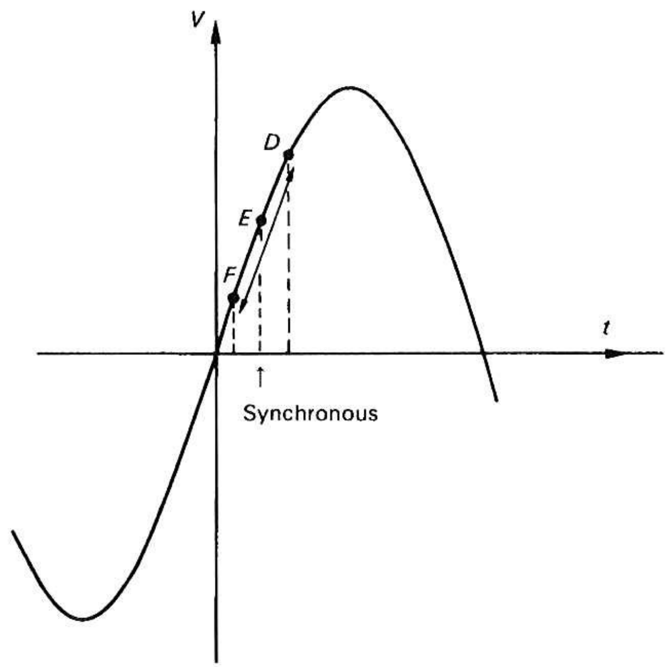
Ref: E. Wilson, CERN

Phase Stability

- In circular accelerator, phase stably locked by synchronizing the phase of the RF voltage (rising or falling) as particle crosses an accelerating gap

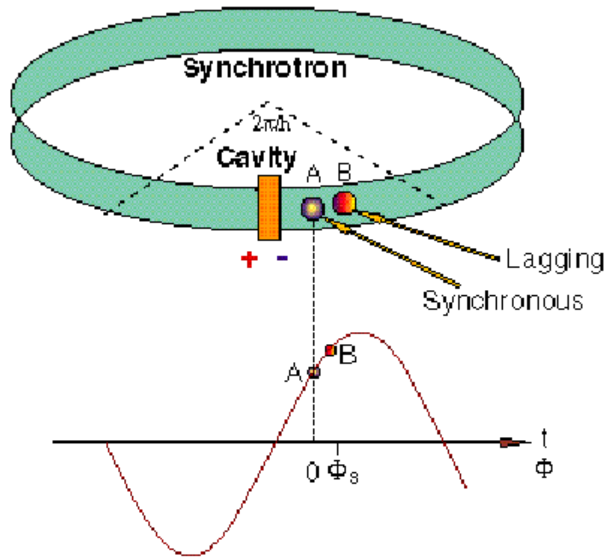
- Synchrotron oscillations about a stable phase results
  - synchrotron oscillations

    (longitudinal oscillations)

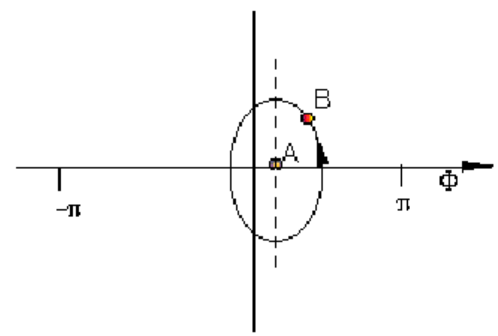


Phase Stability

- Particles are trapped in an "RF bucket"



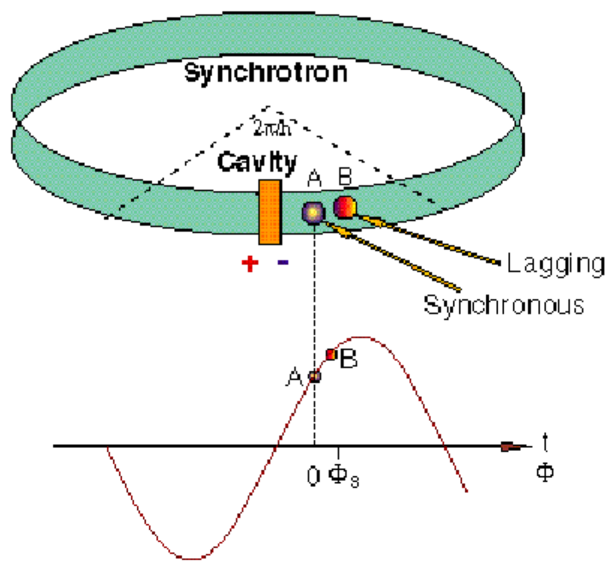
$$V = V_0 \sin(2\pi f_a + \phi_s)$$



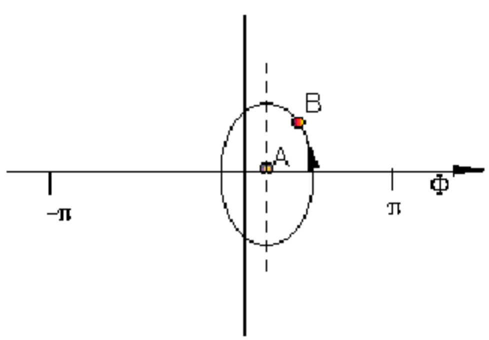
Ref: E. Wilson, CERN

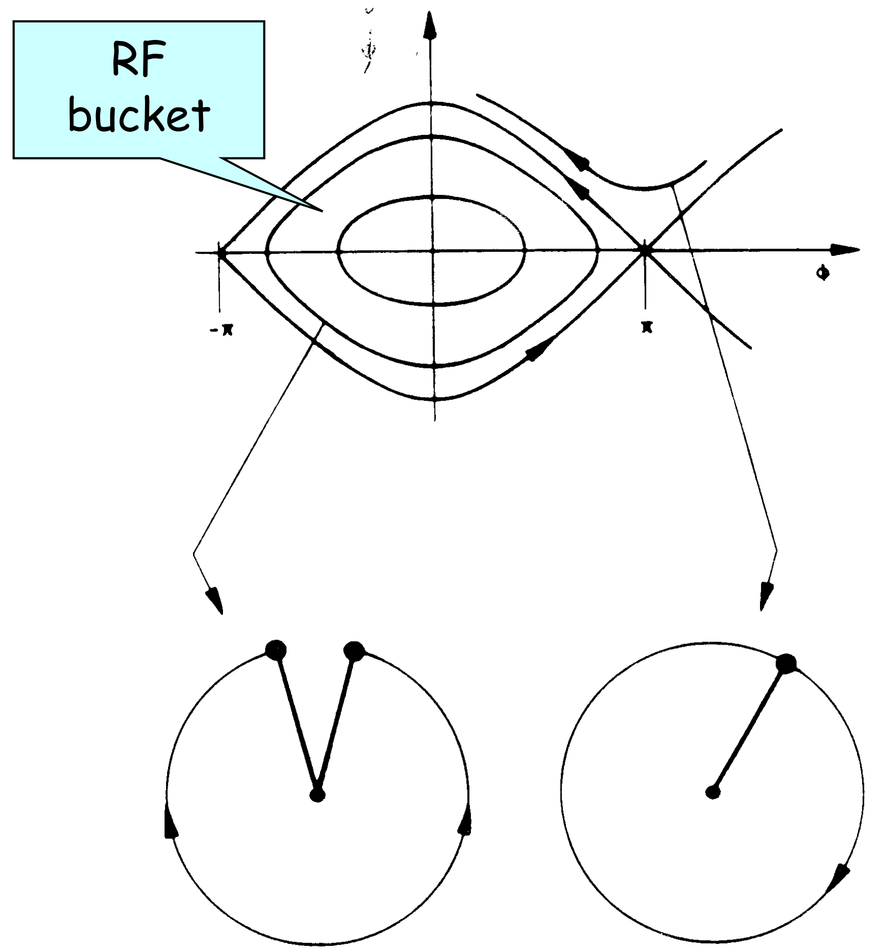
Circular Accelerator Theory - Stability

- Longitudinal stability (synchrotron oscillations)



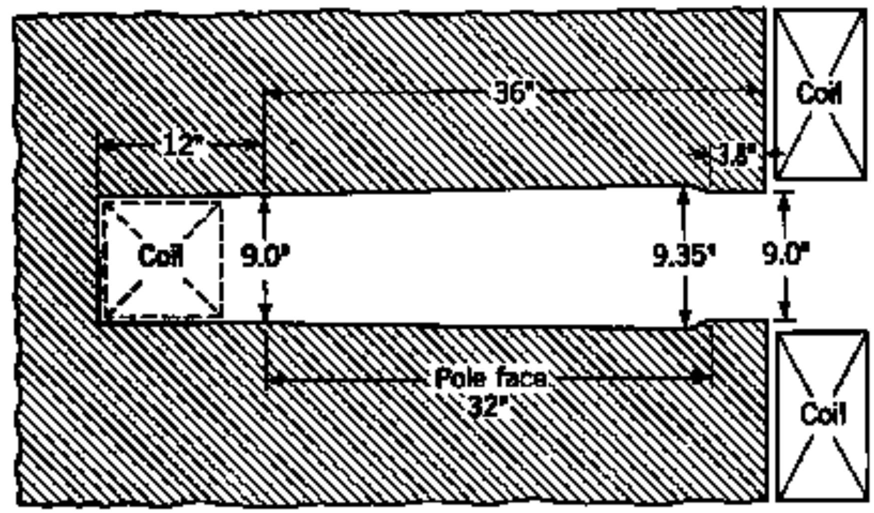
$$V = V_0 \sin(2\pi f_a + \phi_s)$$



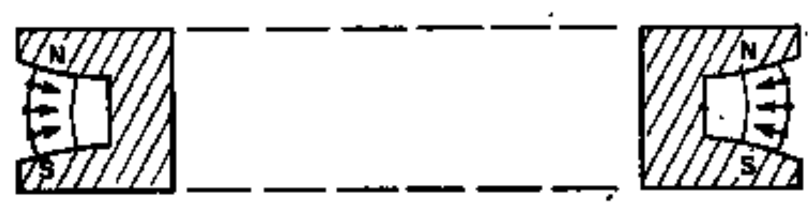


Weak focusing

- Vertical focussing from the curvature of the field lines when the field falls off with radius
- Horizontal focusing from the curvature of the path
- The negative field gradient defocuses horizontally and must not be so strong as to cancel curvature effect

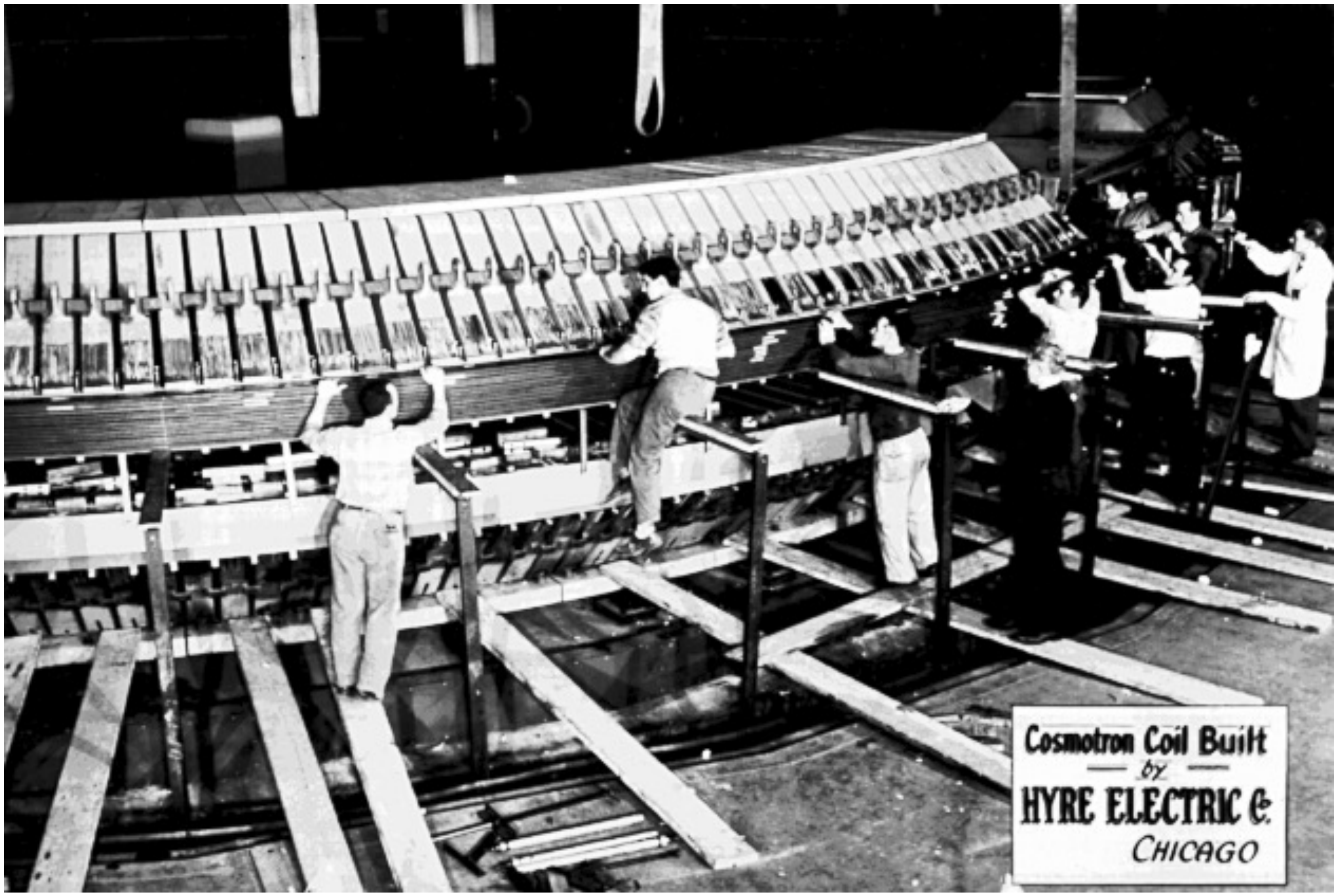


The Cosmotron magnet

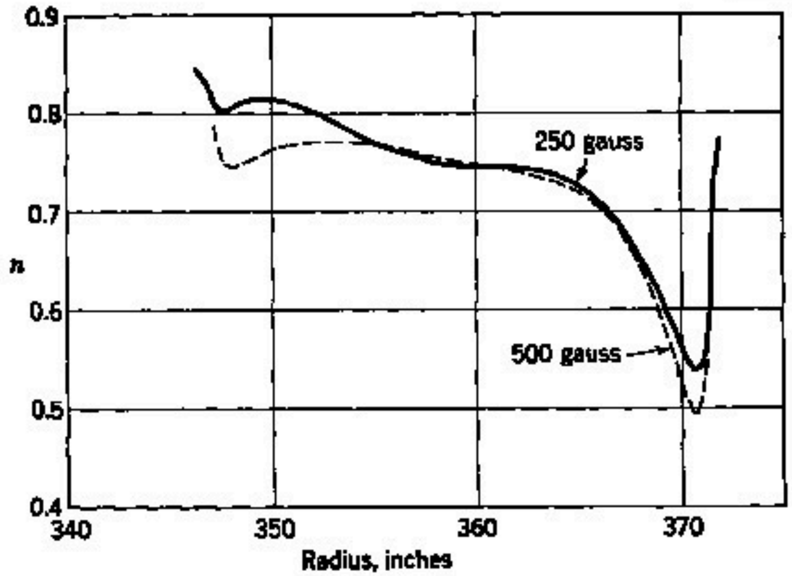


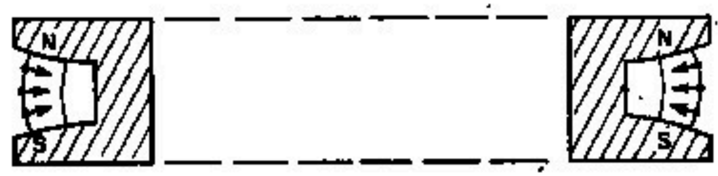
Ref: E. Wilson, CERN

Cosmotron



Weak focusing





$$B_z = B_0\left(1 - n\frac{\Delta r}{r_0}\right) \qquad n = -\frac{r}{B}\frac{\partial B}{\partial r}$$

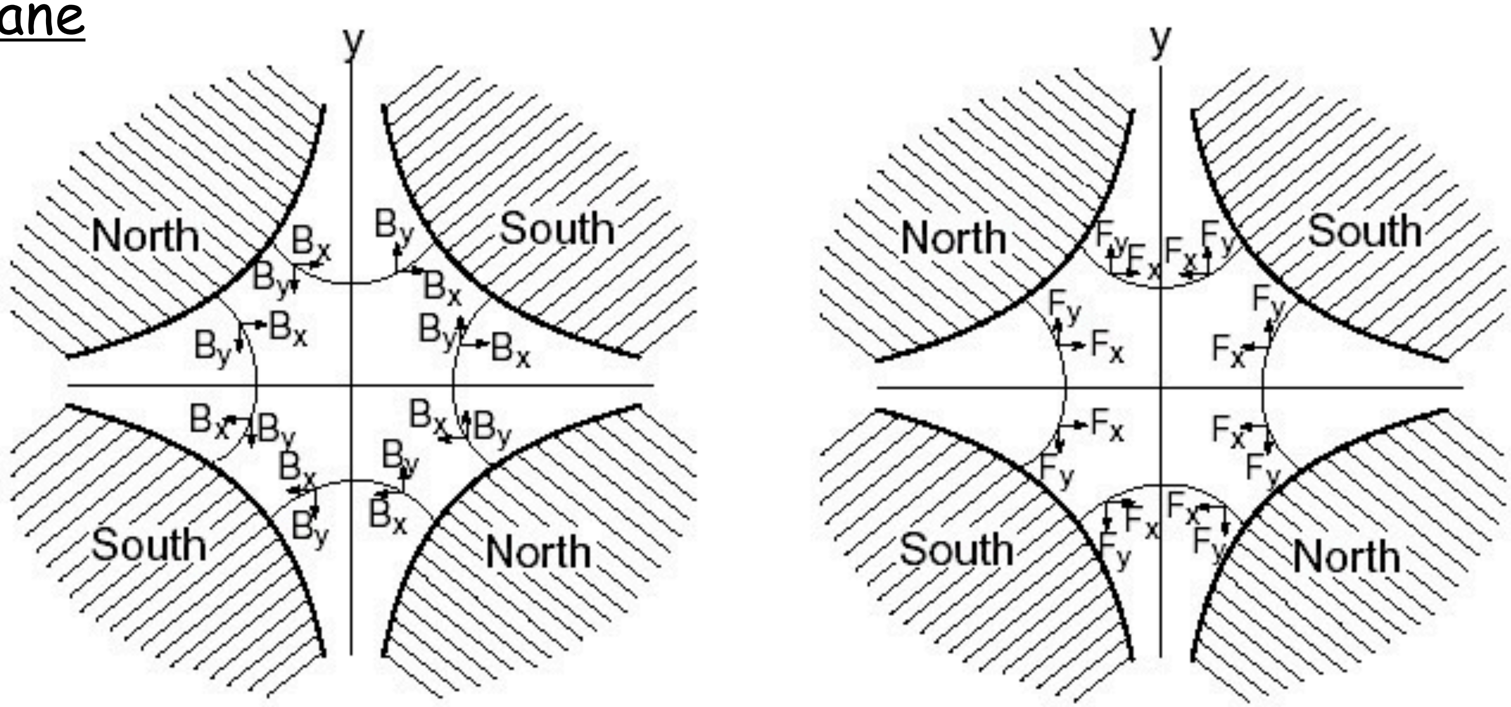
$$f_r = f_0(1-n)^{1/2} \qquad f_z = f_0 n^{1/2}$$

$$\text{Stable if: } \quad 0 < n < 1$$ (weak)

Ref: E. Wilson, CERN

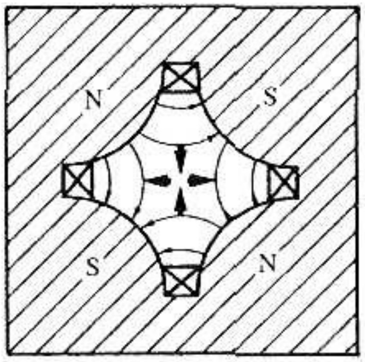
Quadrupole

- The principal focusing element used today in synchrotrons is the quadrupole magnet
- The quadrupole shown below would <u>focus in the horizontal plane</u> positive particles coming out or negative particles going in. Such a quadrupole is <u>defocusing in the vertical plane</u>



Strong focusing

- Alternating diverging and focusing lenses separated by finite distance results in net focusing

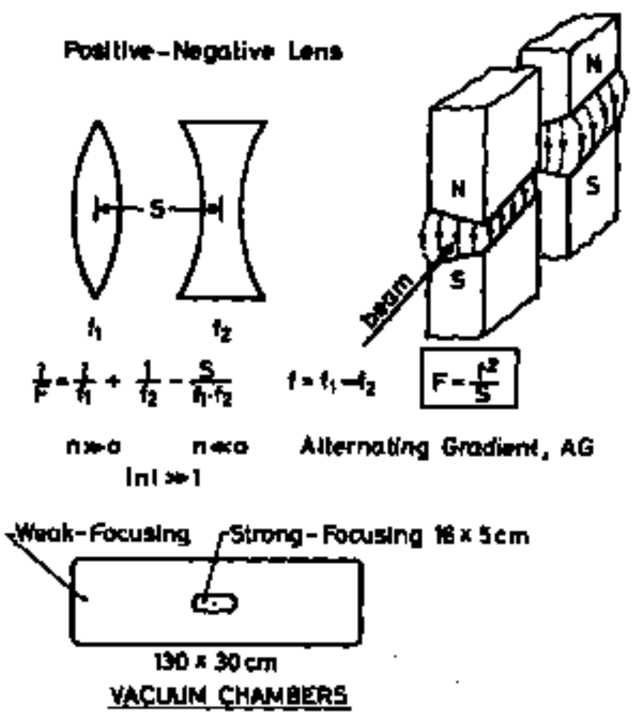


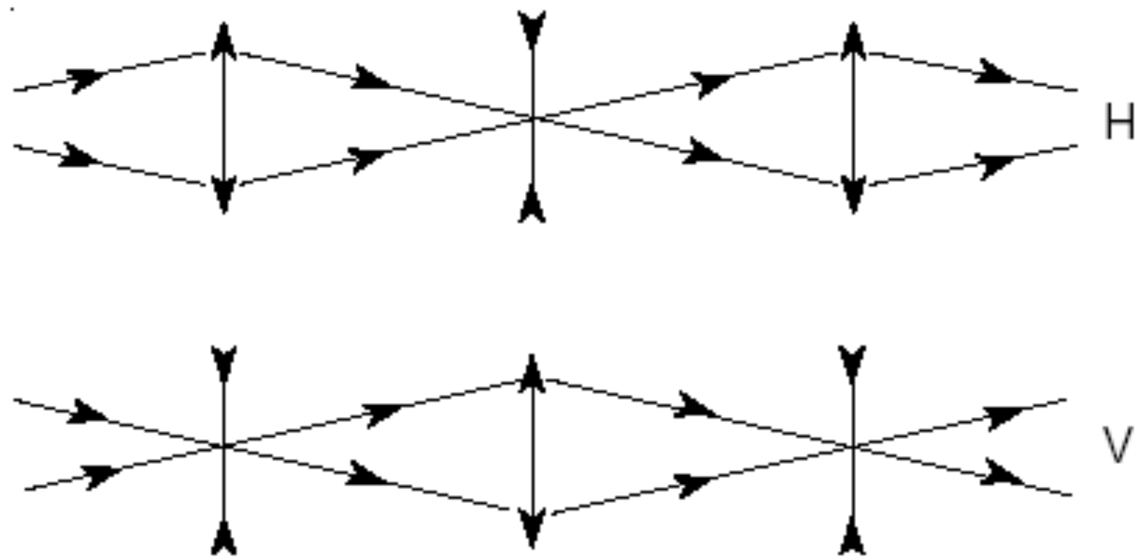
- Magnetic quadrupole focuses in one plane and defocuses in orthogonal plane

- Alternating quadrupoles focus in both planes
  - much stronger than focussing of solenoids of radial magnetic gradients (dipoles)
  - decreases aperture required for stability
  - greatly extends energy range of acceleration

Strong Focusing

- Ray diagrams showing the contained trajectory in an alternating gradient optical system
- An alternating pattern of lenses which are convex in one plane and concave in the other will transport rays which <u>pass through the centres of defocusing lenses</u>. The upper diagram shows the horizontal motion and the lower shows the vertical





Ref: E. Wilson, CERN

Betatron Oscillations

21.3.1. ***Betatron oscillations:***

Present-day high-energy accelerators employ alternating gradient focussing provided by quadrupole magnetic fields [1]. The equations of motion of a particle undergoing oscillations with respect to the design trajectory are

$$x'' + K_x(s)\,x = 0 \ , \quad y'' + K_y(s)\,y = 0 \ , \qquad \text{(transverse)} \tag{21.5}$$

with

$$x' \equiv dx/ds \ , \quad y' \equiv dy/ds \tag{21.6}$$

$$K_x \equiv B'/(B\rho) + \rho^{-2} \ , \quad K_y \equiv -B'/(B\rho) \tag{21.7}$$

$$B' \equiv \partial B_y/\partial x \ . \tag{21.8}$$

The independent variable s is path length along the design trajectory. This motion is called a *betatron* oscillation because it was initially studied in the context of that type of accelerator. The functions K_x and K_y reflect the transverse focussing—primarily due to quadrupole fields except for the radius of curvature, ρ, term in K_x for a synchrotron—so each equation of motion resembles that for a harmonic oscillator but with spring constants that are a function of position. No terms relating to synchrotron oscillations appear, because their time scale is much longer and in this approximation play no role.

from Particle Data Group

Betatron Oscillations

These equations have the form of Hill's equation and so the solution in one plane may be written as

$$x(s) = A\sqrt{\beta(s)}\ \cos(\psi(s) + \delta), \tag{21.9}$$

where A and δ are constants of integration and the phase advances according to $d\psi/ds = 1/\beta$. The dimension of A is the square root of length, reflecting the fact that the oscillation amplitude is modulated by the square root of the amplitude function. In addition to describing the envelope of the oscillation, β also plays the role of an 'instantaneous' $\lambda\!\!\!^{-}$. The wavelength of a betatron oscillation may be some tens of meters, and so typically values of the amplitude function are of the order of meters rather than on the order of the beam size. The beam optics arrangement generally has some periodicity and the amplitude function is chosen to reflect that periodicity. As noted above, at the interaction point a small value of the amplitude function is desired, and so the focussing optics is tailored in the neighborhood to provide a suitable β^*.

The number of betatron oscillations per turn in a synchrotron is called the *tune* and is given by

TUNE

$$\nu = \frac{1}{2\pi}\oint\frac{ds}{\beta}\ . \tag{21.10}$$

Betatron Oscillations

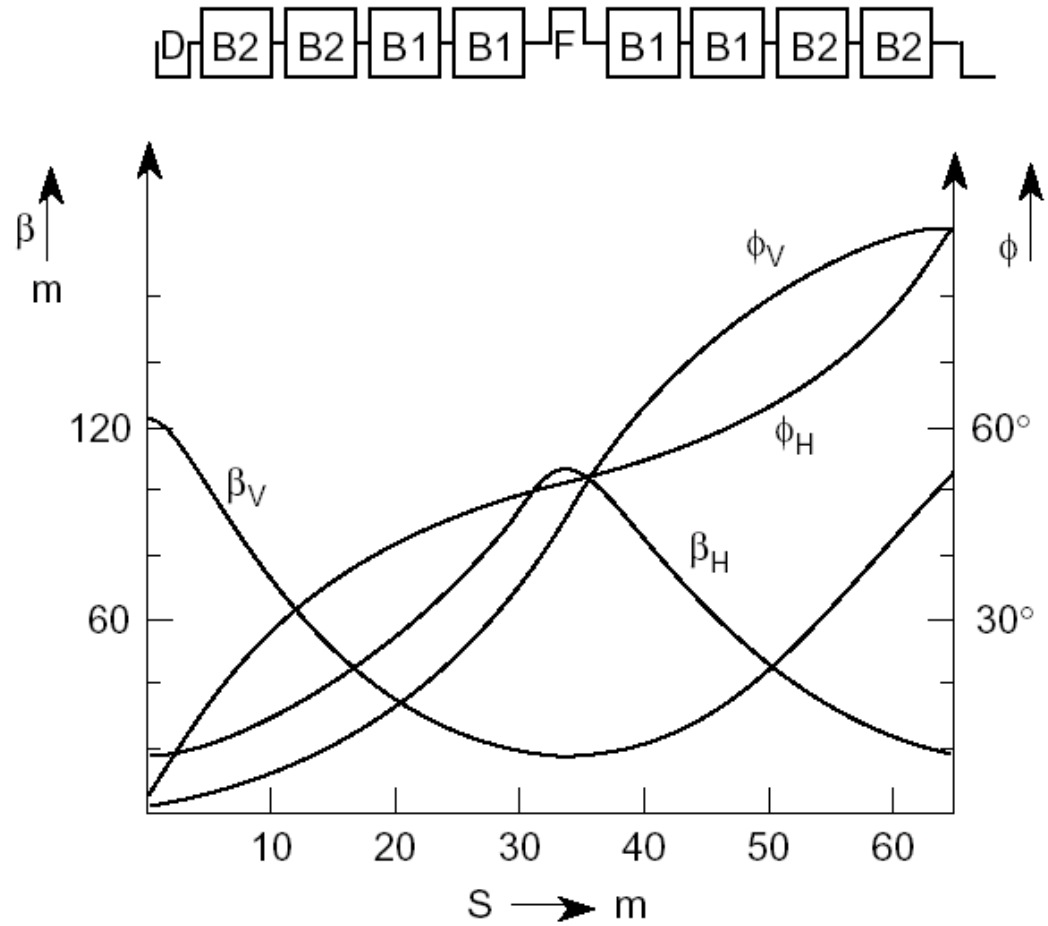
- betatron oscillations

$$x(s) = A\sqrt{\beta(s)}\ \cos(\psi(s) + \delta),$$

- phase (ψ) advances as $1/\beta = d\psi/ds$
- β^* (wavelength at IP, want to minimize)
- tune: $\nu = \frac{1}{2\pi}\oint \frac{ds}{\beta}$

FODO cells

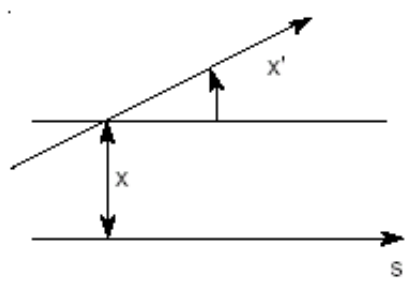
- Quadrupole magnets alternate with a the lattice of bending magnets
- Structure is called FODO.
- The envelope of oscillations follows the function β(*s*)
- β has the dimensions of length, but is not the physical beam size.

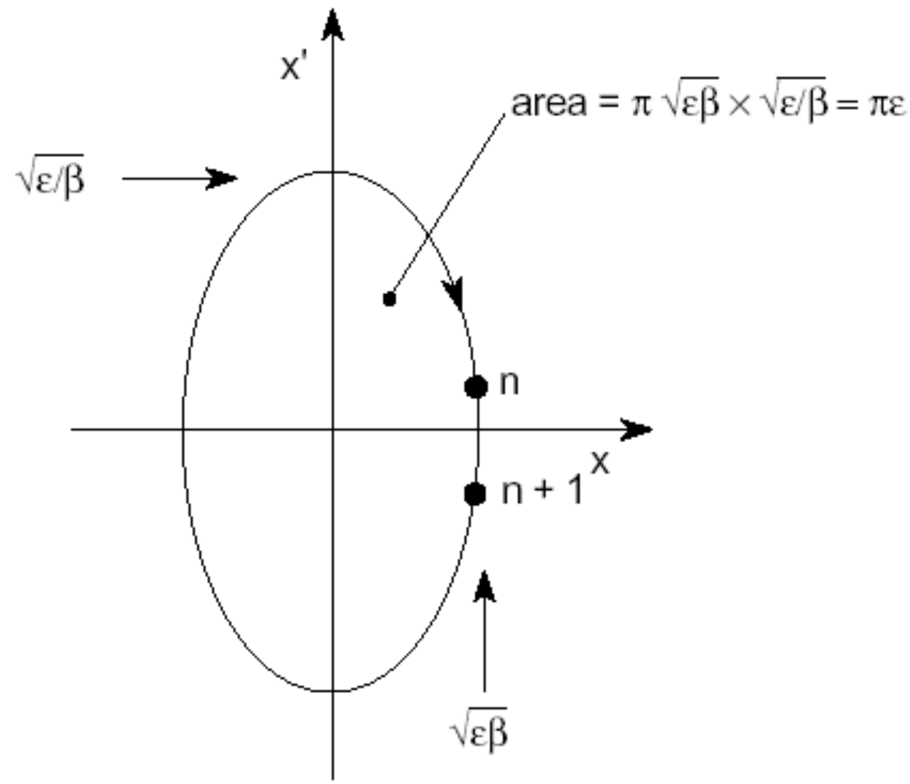


One cell of the CERN SPS representing 1/108 of the circumference.

Particle trajectories

The beam size can be expressed in terms of two quantities, the *transverse emittance*, ε, and the *amplitude function*, β.





- The coordinates (x, x′) of particles in the beam will fall in the range:

$$-\sqrt{\beta\varepsilon} \le x \le \sqrt{\beta\varepsilon}$$
$$-\sqrt{\varepsilon/\beta} \le x' \le \sqrt{\varepsilon/\beta}$$

- β is a property of the accelerator

- ε is a property of the beam

Circular Accelerator Theory - Stability

- Betatron oscillations (transverse oscillations)

$$x(s) = A\sqrt{\beta(s)}\ \cos(\psi(s) + \delta),$$

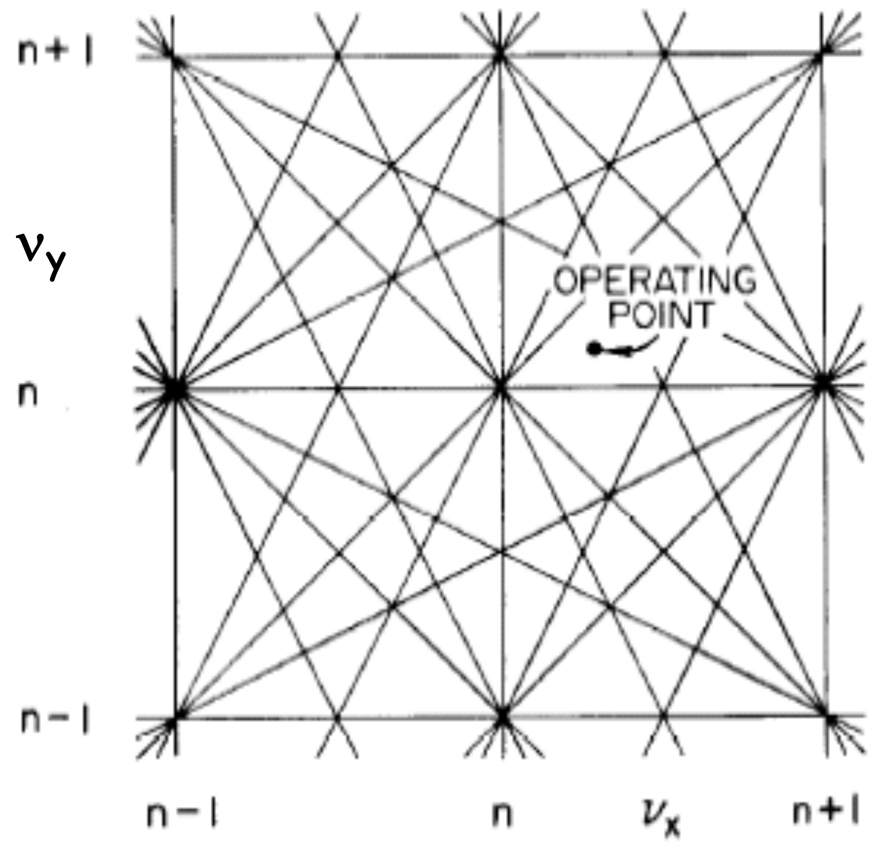
$1/\beta = d\psi/ds$

- Tune: $$\nu = \frac{1}{2\pi}\oint \frac{ds}{\beta}$$

- Resonances (particularly critical for storage rings):
  - If ν is an integer, tiny perturbations will drive beam out of stable orbit
    - eg. the smallest imperfection in the guide field
      (and there will surely be at least one!)
      will act as a perturbation which is synchronous with the oscillation frequency.
  - More generally, a resonance occurs when $m\nu_x + n\nu_y = r$, for integers m, n, and r.

Storage Ring - Stability

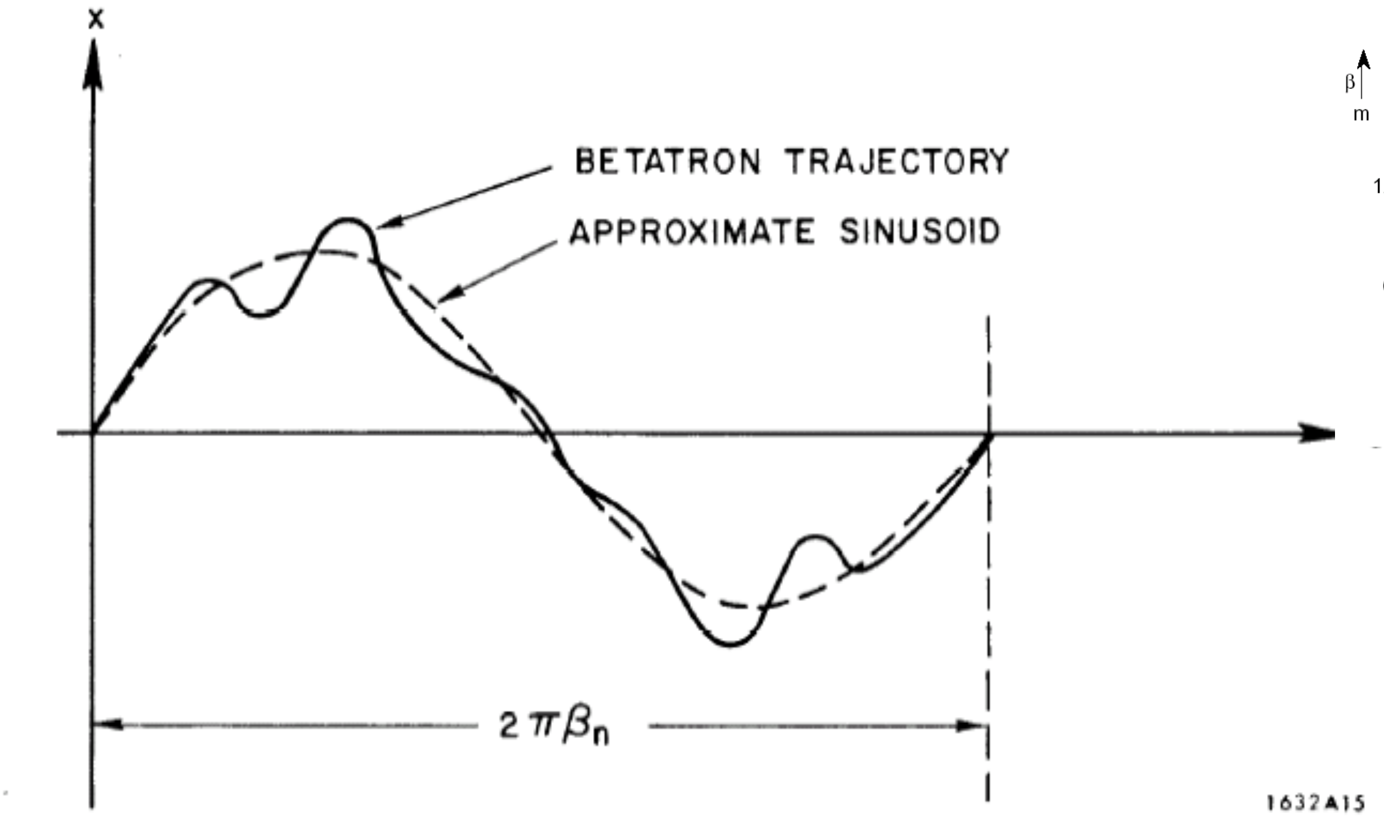
- A resonance occurs when for certain "tunes" $m\nu_x + n\nu_y = r$, for integers m, n, and r.
- Significant effects are usually observed for small integers
- The operating point of a storage ring is specified by giving both ν_x and ν_y and must be chosen to avoid the serious resonances.

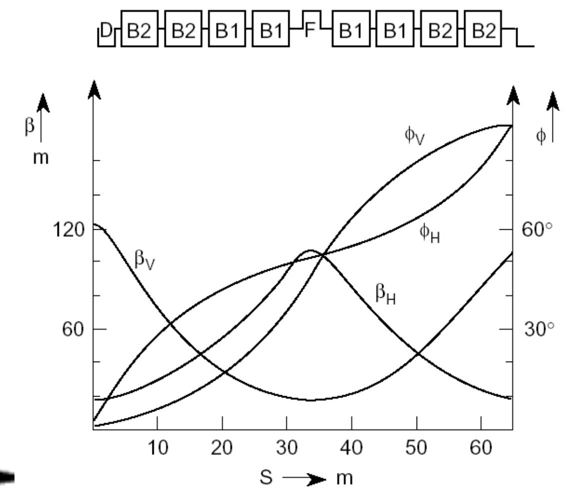


Storage Ring - Typical Orbit

$$x = A\cos(s/\beta_n + \theta)$$

$$\oint \frac{ds}{\beta} = \frac{L}{\beta_n}$$





Storage Ring - Tune Shift

- The field gradient in the storage ring is never the ideal of the design.
- These gradient errors change the function of the betatron oscillations from the ideal orbit.
- And the betatron number is changed from its nominal value ν, to another value, $\nu + \Delta\nu$. ($\Delta\nu$ is called the tune shift)
- The tune shift $\Delta\nu$ must be controlled to keep the operating point away from resonances.

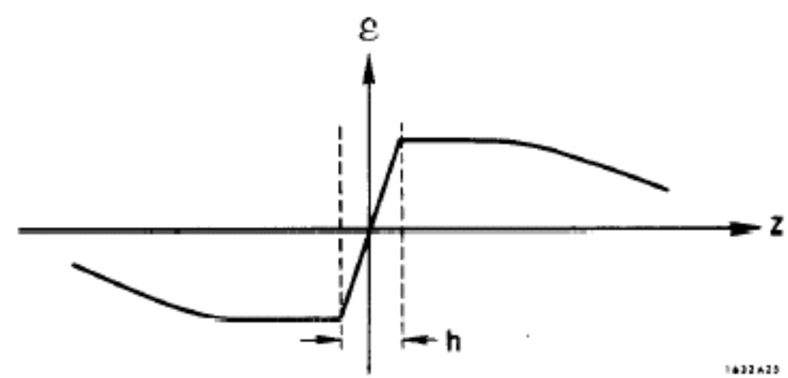
$$2\pi\,\Delta\nu = -\oint \frac{\Delta\beta(s)}{\beta^2}\,ds$$

- BEAM-BEAM TUNE SHIFT

$$\Delta\nu_y = \frac{r_e}{2\pi}\,\frac{N_B\beta_z^*}{\gamma\sigma_z(\sigma_x+\sigma_z)}$$

$$\Delta\nu_x = \frac{r_e}{2\pi}\,\frac{N_B\beta_x^*}{\gamma\sigma_x(\sigma_z+\sigma_x)}$$

$$r_e = \frac{e^2}{4\pi\,\epsilon_0 mc^2}$$



Summary of Accelerator Concepts

- synchrotron oscillations
  - Longitudinal oscillation of particles about an equilibrium of the phase of accelerating voltage
  - The restoring force for the oscillation is provided by out of time particles receiving greater or less acceleration (phase focusing)
  - Particles typically makes many revolutions around the accelerator in a single synchrotron oscillation period
- betatron oscillations
  - Transverse oscillation of particles in a circular accelerator about the equilibrium orbit
  - The restoring force for the oscillation is provided by focusing components in the magnetic field which bends a particle that is off the equilibrium orbit back toward it
  - modern (strong focusing) designs create several cycles of betatron oscillation per revolution of beam particles
- tune
  - The number of betatron oscillations per revolution of the beam
- strong focusing
  - system for focusing charged particles in which the particles pass alternately through non-uniform electric or magnetic fields having gradients of opposite sign

Based on glossary of accelerator terms compiled by Fermilab Accelerator Division Operations Dept.

Luminosity

- If two bunches containing n_1 and n_2 particles collide with frequency f, then the luminosity is

$$\mathscr{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

- But recall beam size is a function of the tranverse emittance, ε, and the β function

$$\epsilon = \pi\sigma^2/\beta$$

- So

$$\mathscr{L} = f \frac{n_1 n_2}{4\sqrt{\epsilon_x\,\beta_x^*\,\epsilon_y\,\beta_y^*}}$$

Luminosity Lifetime

$$\mathscr{L} = f \frac{n_1 n_2}{4\sqrt{\epsilon_x \, \beta_x^* \, \epsilon_y \, \beta_y^*}}$$

Storage ring luminosity lifetime is limited by:

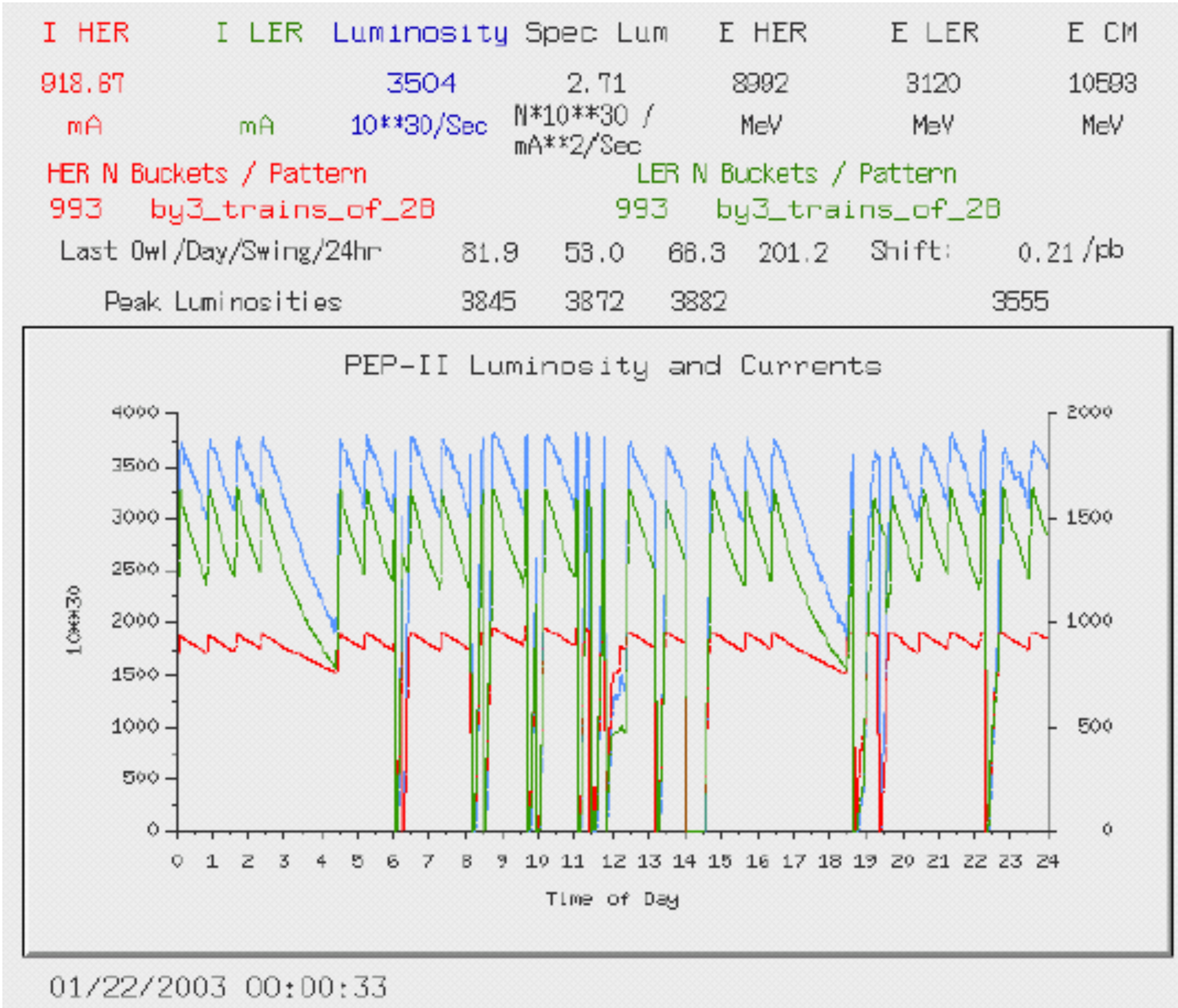
- interactions of the two beams at the IPs
- beam size blowup due to intra-beam scattering
- reduction in the beam intensity due to rest gas scattering
- beam size reduction due to synchrotron radiation damping
- beam size blowup due to the non-linear beam-beam interactions

Different effects will dominate
in different colliders

Future Super-B Factory
(requires continuous injection)

Lifetime Contribution	HER	LER
Luminosity lifetime (min)	15	58
Vacuum lifetime (min)	100	30
Touschek lifetime (min)	300	30
Beam-beam tune shift lifetime (min)	10	10
Dynamic aperture lifetime (min)	20	20
Overall lifetime (min)	4.4	4.1

Luminosity Lifetime - PEP II



Luminosity Lifetime - continuous injection

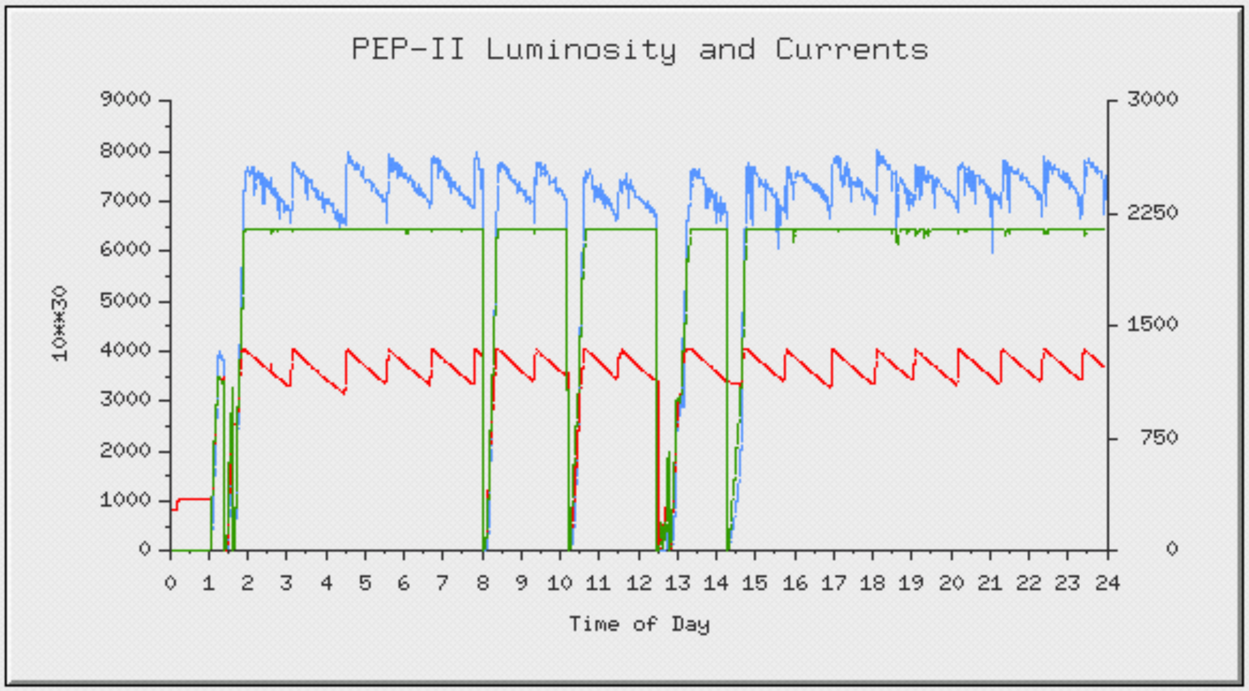
I HER	I LER	Luminosity	Spec Lum	E HER	E LER	E CM
1213.53	2149.17	7423	3.90	8923	3119	10551
mA	mA	10**30/Sec	N*10**30 / mA**2/Sec	MeV	MeV	MeV

HER N Buckets / Pattern LER N Buckets / Pattern

1369 by2_t14_t15_her_no_fb_m 1369 by2_t14_t15_ler_no_fb_m

Last Owl/Day/Swing/24hr 152.3 142.0 201.5 495.8 Shift: 0.44 /pb

Peak Luminosities 8022 7878 8091 7493



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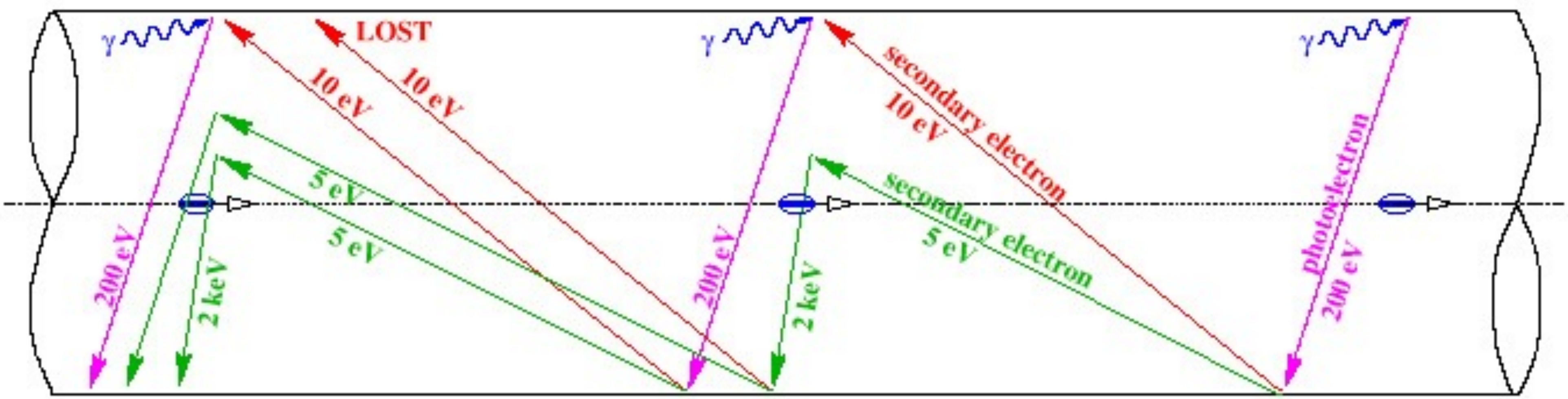
Electron Cloud Effect

- The build up of the charge of electrons emitted from the walls of the beampipe can limit the performance of an acclerator – the Electron Cloud Effect
- Various strategies have been developed to minimize this effect



F. Ruggiero

Table 2.2: LHC beam parameters relevant for the luminosity lifetime

		Injection	Collision
Interaction data			
Inelastic cross section	[mb]	60.0	
Total cross section	[mb]	100.0	
Events per bunch crossing		-	19.02
Beam current lifetime (due to beam-beam)	[h]	-	44.86
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	$[10^{-4}]$	3.06	1.129
RMS bunch length	[cm]	11.24	7.55
Longitudinal emittance growth time	[hours]	30[a]	61
Horizontal emittance growth time	[hours]	38[a]	80
Total beam and luminosity lifetimes[b]			
Luminosity lifetime (due to beam-beam)	[hours]	-	29.1
Beam lifetime (due to rest-gas scattering)[c]	[hours]	100	100
Beam current lifetime (beam-beam, rest-gas)	[hours]	-	18.4
Luminosity lifetime (beam-beam, rest-gas, IBS)	[hours]	-	14.9
Synchrotron Radiation			
Instantaneous power loss per proton	[W]	3.15×10^{-16}	1.84×10^{-11}
Power loss per m in main bends	$[\mathrm{Wm}^{-1}]$	0.0	0.206
Synchrotron radiation power per ring	[W]	6.15×10^{-2}	3.6×10^{3}
Energy loss per turn	[eV]	1.15×10^{-1}	6.71×10^{3}
Critical photon energy	[eV]	0.01	44.14
Longitudinal emittance damping time	[hours]	48489.1	13
Transverse emittance damping time	[hours]	48489.1	26

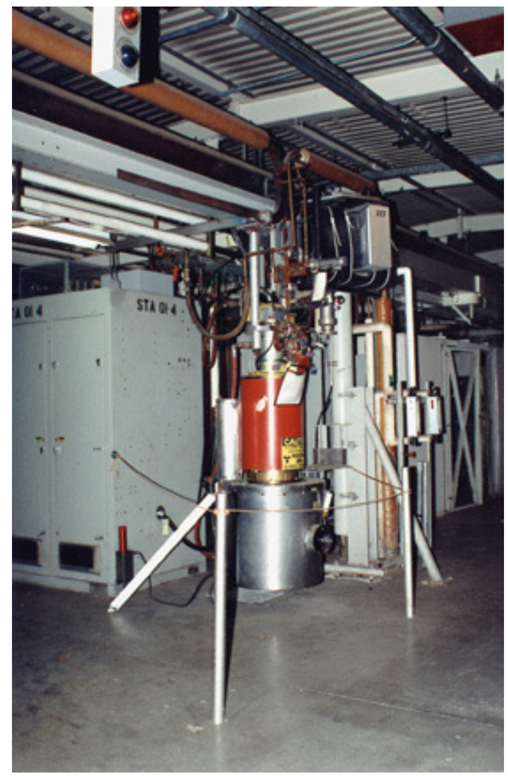
[a] IBS growth times are given without the 200 MHz RF system.

[b] lifetime estimates including the effect of proton losses due to luminosity production, IBS and vacuum rest gas scattering. It is assumed that the effect of the non-linear beam-beam interaction and RF noise are compensated by the synchrotron radiation damping.

[c] The desorption lifetime should be slightly better at injection energy because the cross sections for rest gas scattering decrease with energy. For more information see Vol II, Chap. 28 and [1].

High-impedance Microwave Devices

- EM cavities were invented as a way to generate high voltage at moderate input power
  - Amplifiers
  - Oscillators
  - Cavities
  - Disk-loaded waveguides



Klystrons

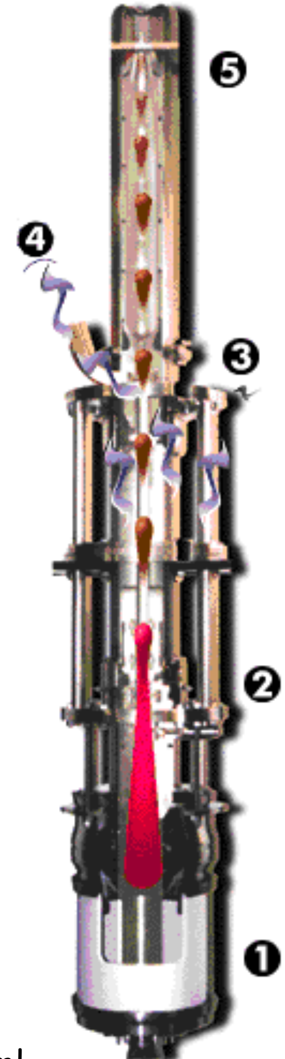
- invented at Stanford in 1937
- served as an oscillator in radar receivers during WW II
- after the war, very high-power klystrons were built at Stanford for use in the first linear accelerators
- Klystrons then were not only used in accelerators and radar, but also in UHF-TV, satellite communications, and industrial heating

Klystron

- high-vacuum device based on the interaction of a well-focused pencil electron beam with a number of microwave cavities that it traverses
- microwave cavities are tuned at or near the operating frequency of the tube
- kinetic energy in the beam, imparted by a high accelerating voltage, converted to microwave energy.
- conversion takes place as a result of the amplified RF input signal, causing the beam to form "bunches"
- energy goes into the high level induced RF fields at the output cavity
- the amplified signal is extracted from the output cavity through a vacuum window

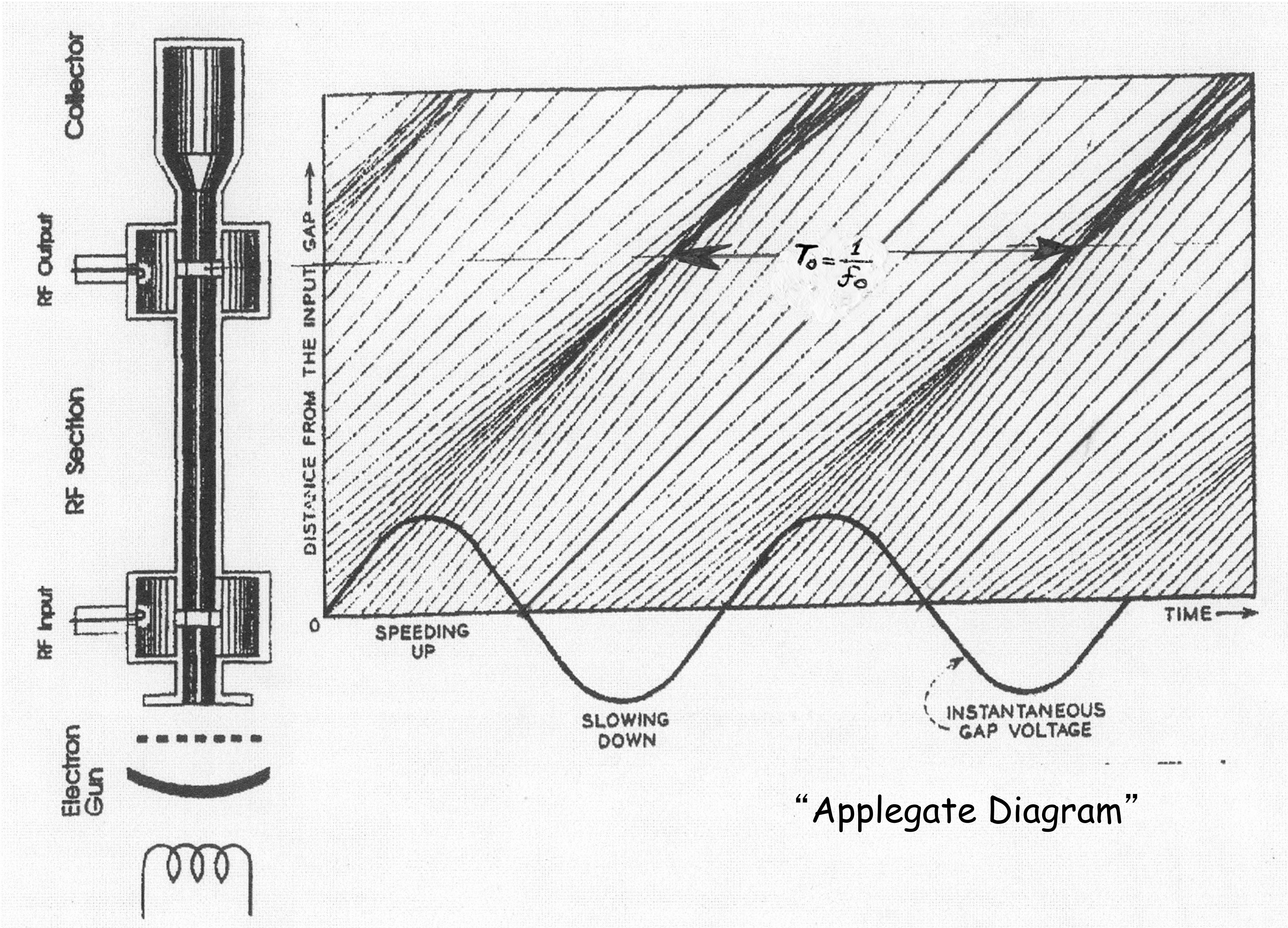
Klystron

The electron gun (1) produces a flow of electrons.
The bunching cavities (2) regulate the speed of the electrons so that they arrive in bunches at the output cavity.
The bunches of electrons excite microwaves in the output cavity (3) of the klystron.
The microwaves flow into the waveguide (4), which transports them to the accelerator.
The electrons are absorbed in the beam stop (5).



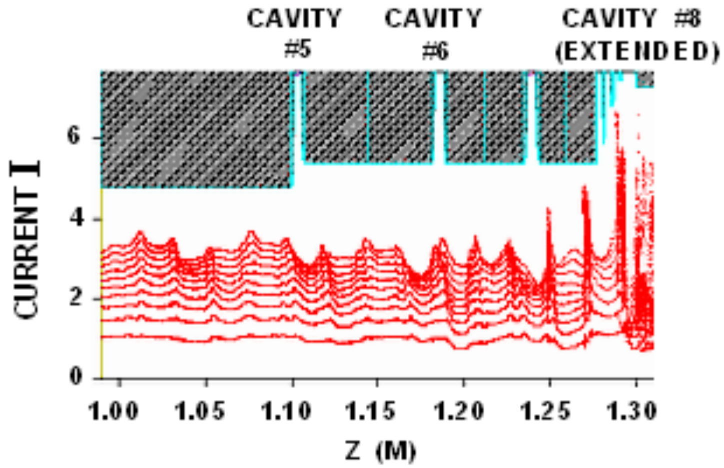
http://www2.slac.stanford.edu/vvc/accelerators/klystron.html

Klystron



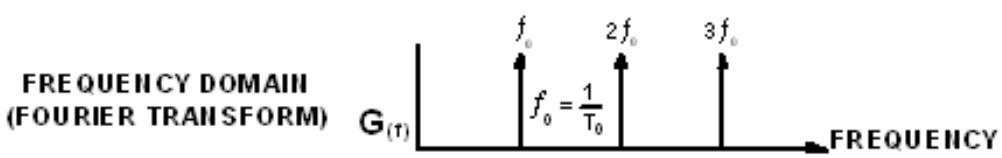
"Applegate Diagram"

Klystron

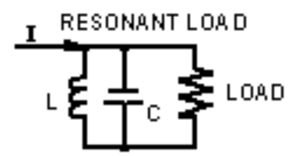


MAGIC SIMULATION (OUTPUT SECTION OF 8-CAVITY PPM KLYSTRON)

CURRENT PULSES INTO OUTPUT CAVITY

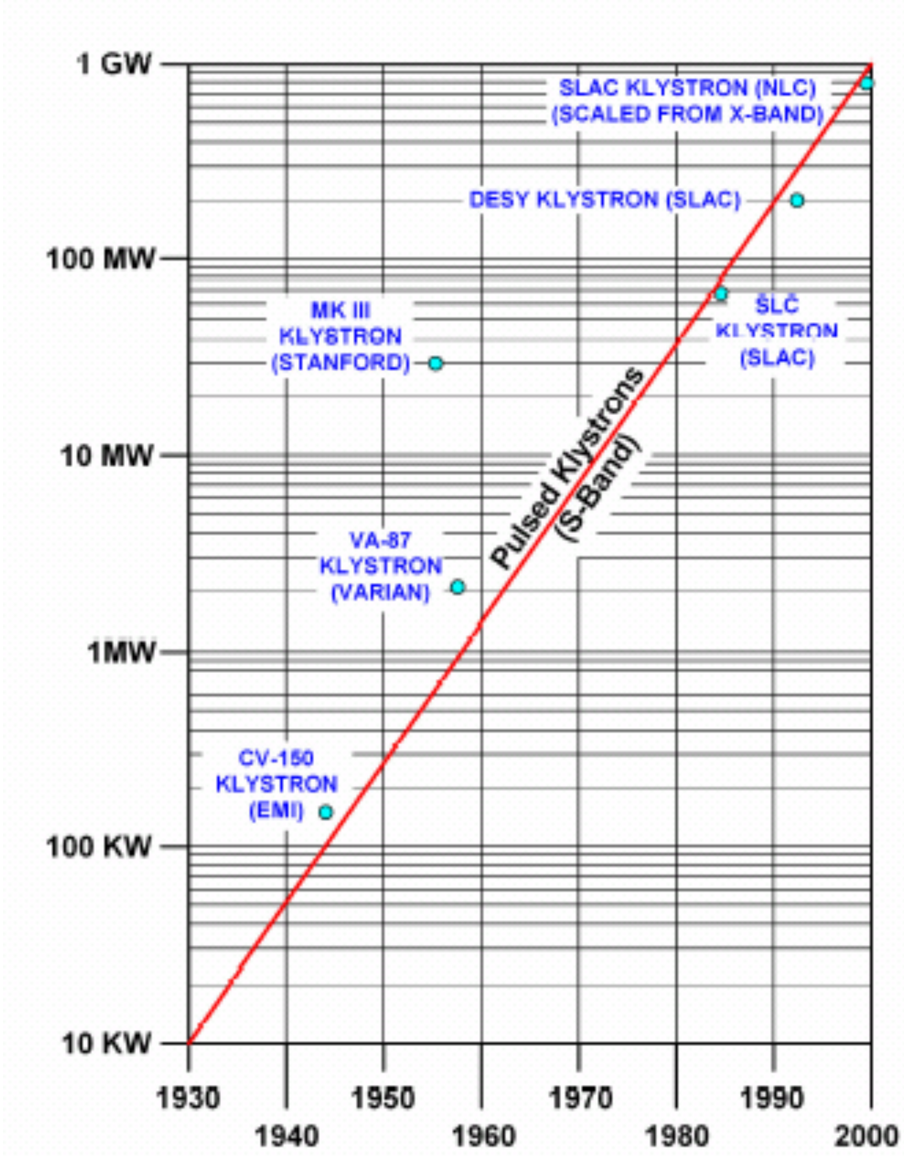


FREQUENCIES INTO OUTPUT CAVITY



$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

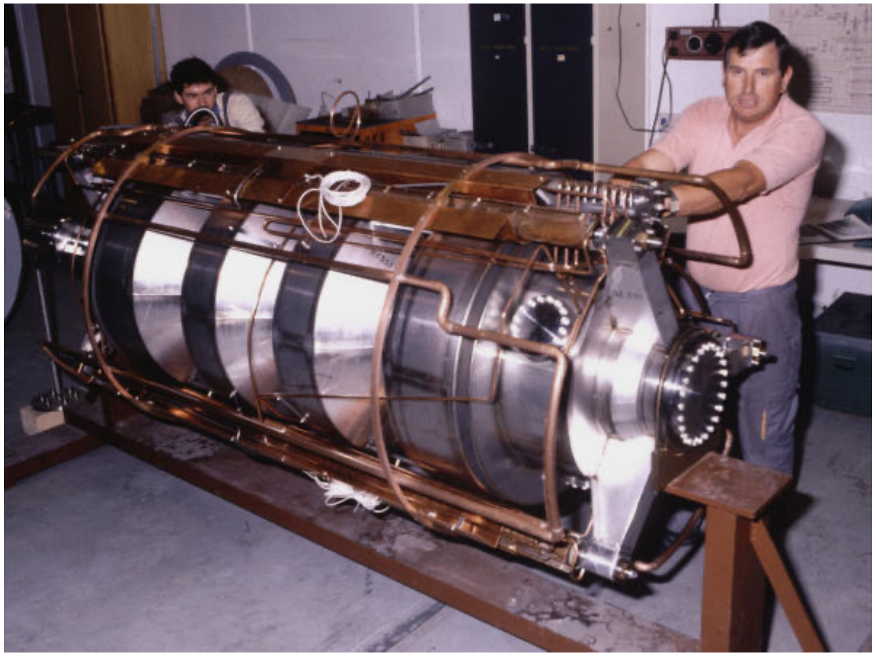
Klystron



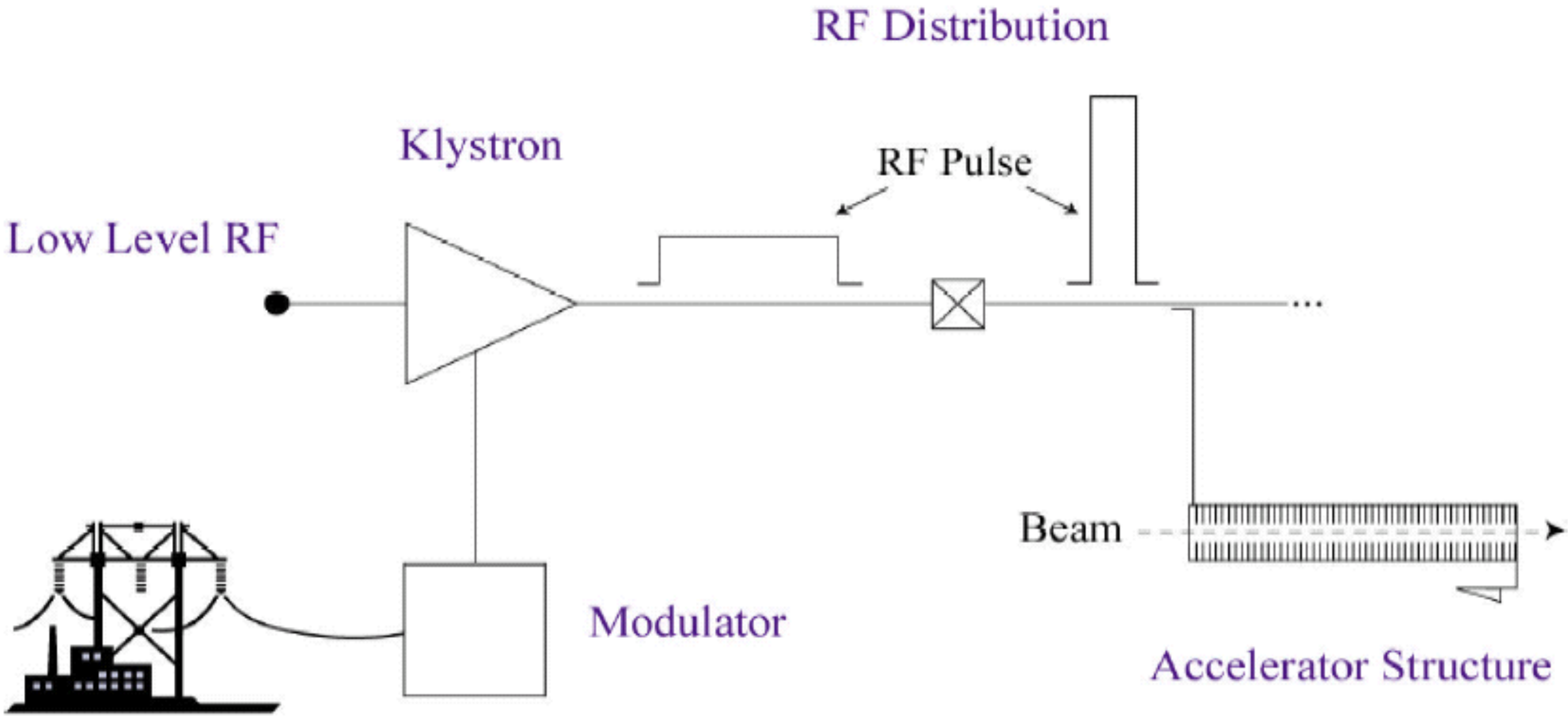
X-Band:
75 Megawatts at 11.4 GHz,
with 1.6 microsecond pulses

Superconducting Technology

- Superconducting materials added to the technology base of accelerators
- Niobium-titanium
  - multistrand cables
  - Niobium-tin for higher fields, but brittle
- Niobium coatings inside RF cavities
  - now practical and reliable

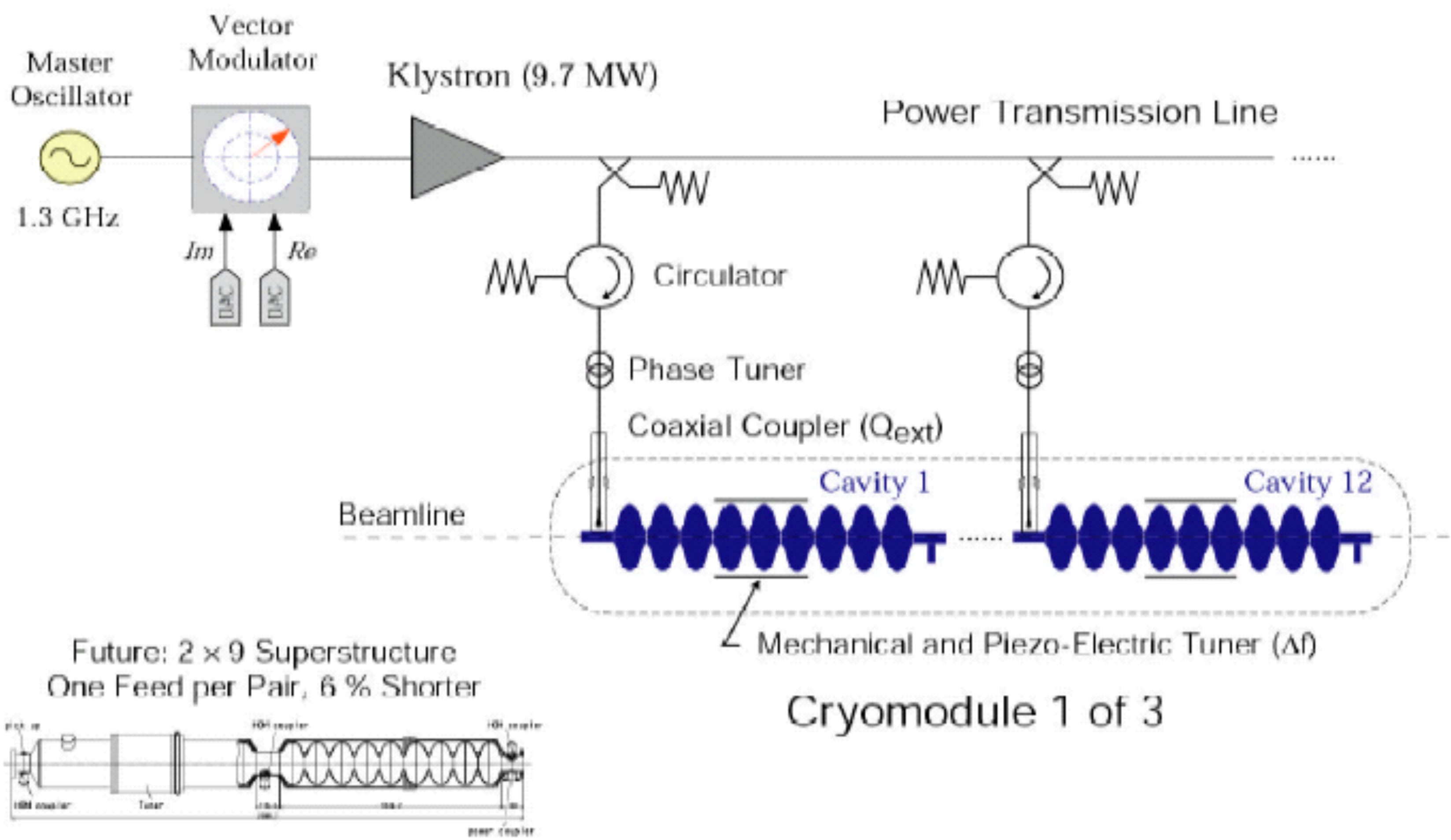


Simplified RF System Accelerator Layout



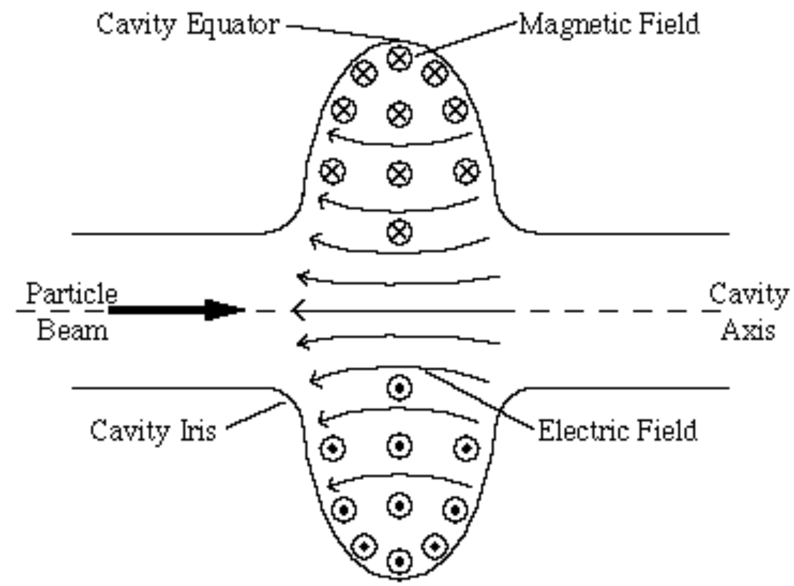
Superconducting RF System

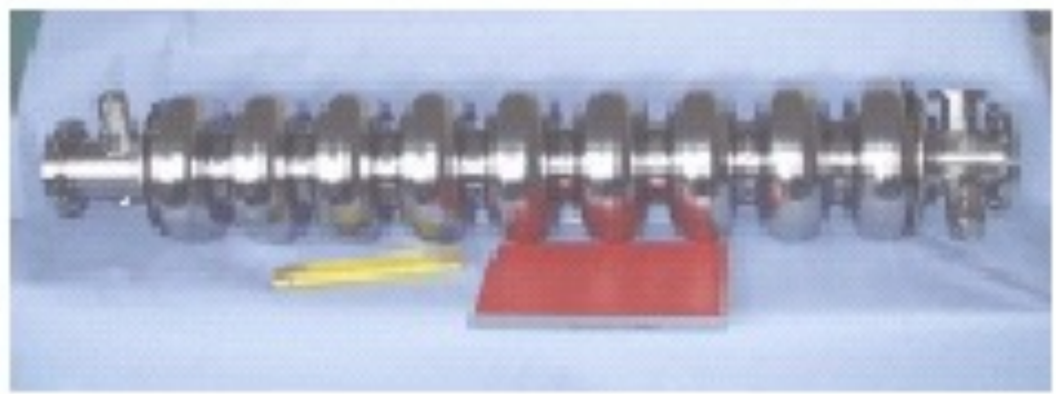
Length = 50 m, Filling Fraction with Quads = 75%



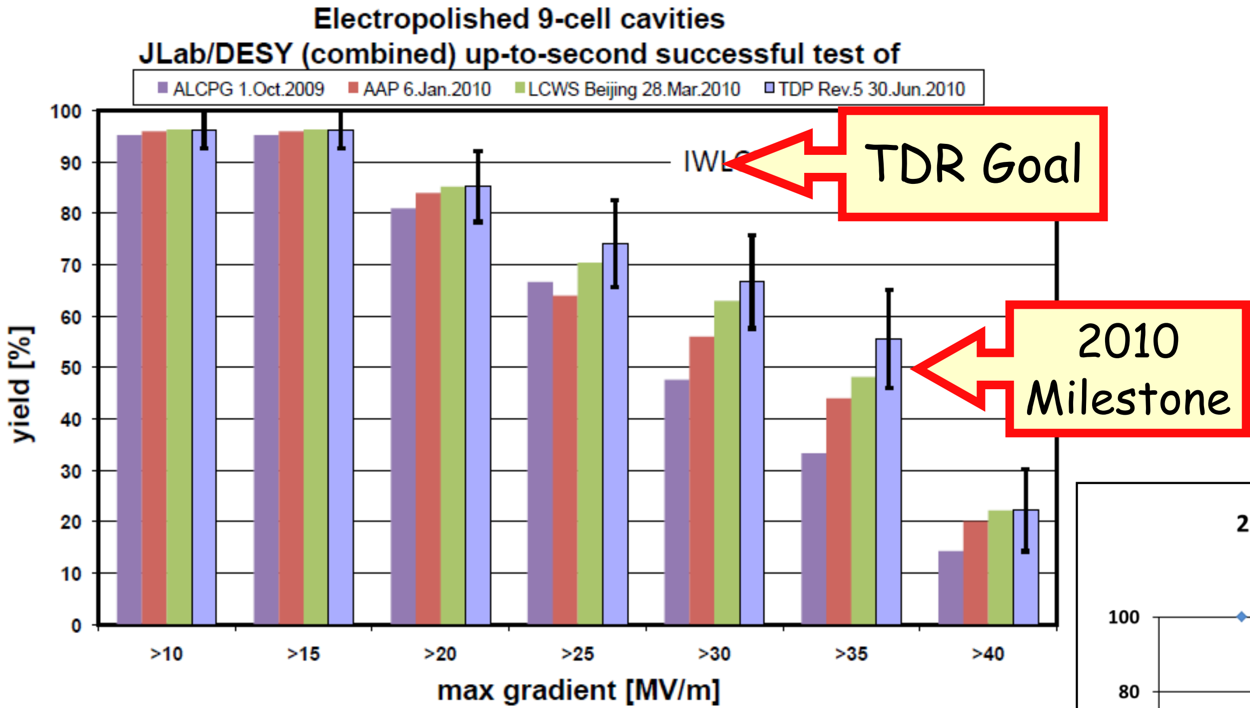
Superconducting RF Accelerating Structure

- Typical cylindrically symmetric cavity, showing the fundamental, or lowest RF frequency, mode (TM 010)
- The electric field is roughly parallel to the beam axis, and decays to zero radially upon approach to the cavity walls.
- Boundary conditions demand that the electric surface be normal to the metal surface.
- The peak surface electric field is located near the iris, or region where the beam tube joins the cavity.
- The magnetic field is azimuthal, with the highest magnetic field located near the cavity equator. The magnetic field is zero on the cavity axis.

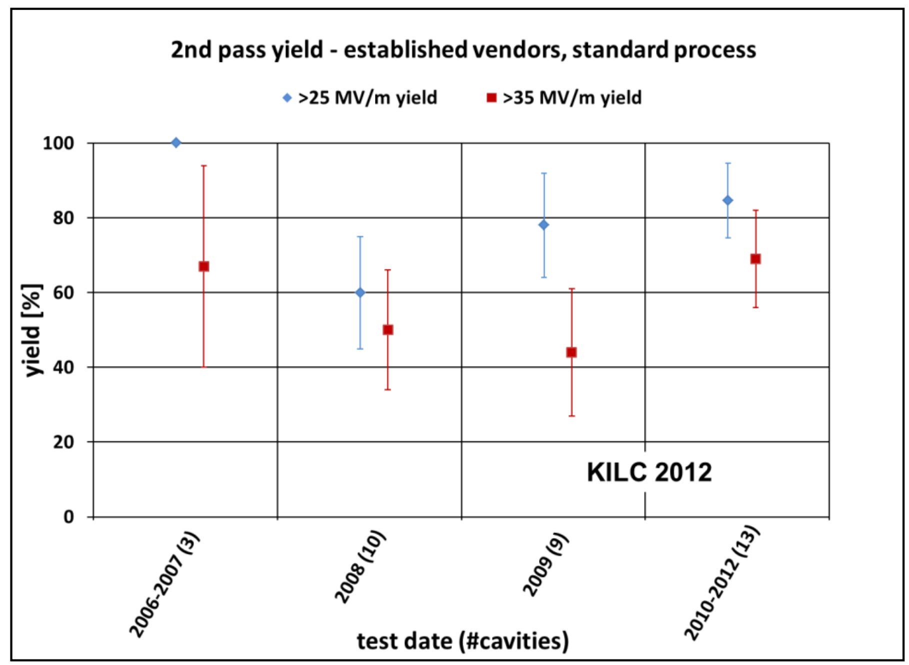




Cavity Gradient Progress



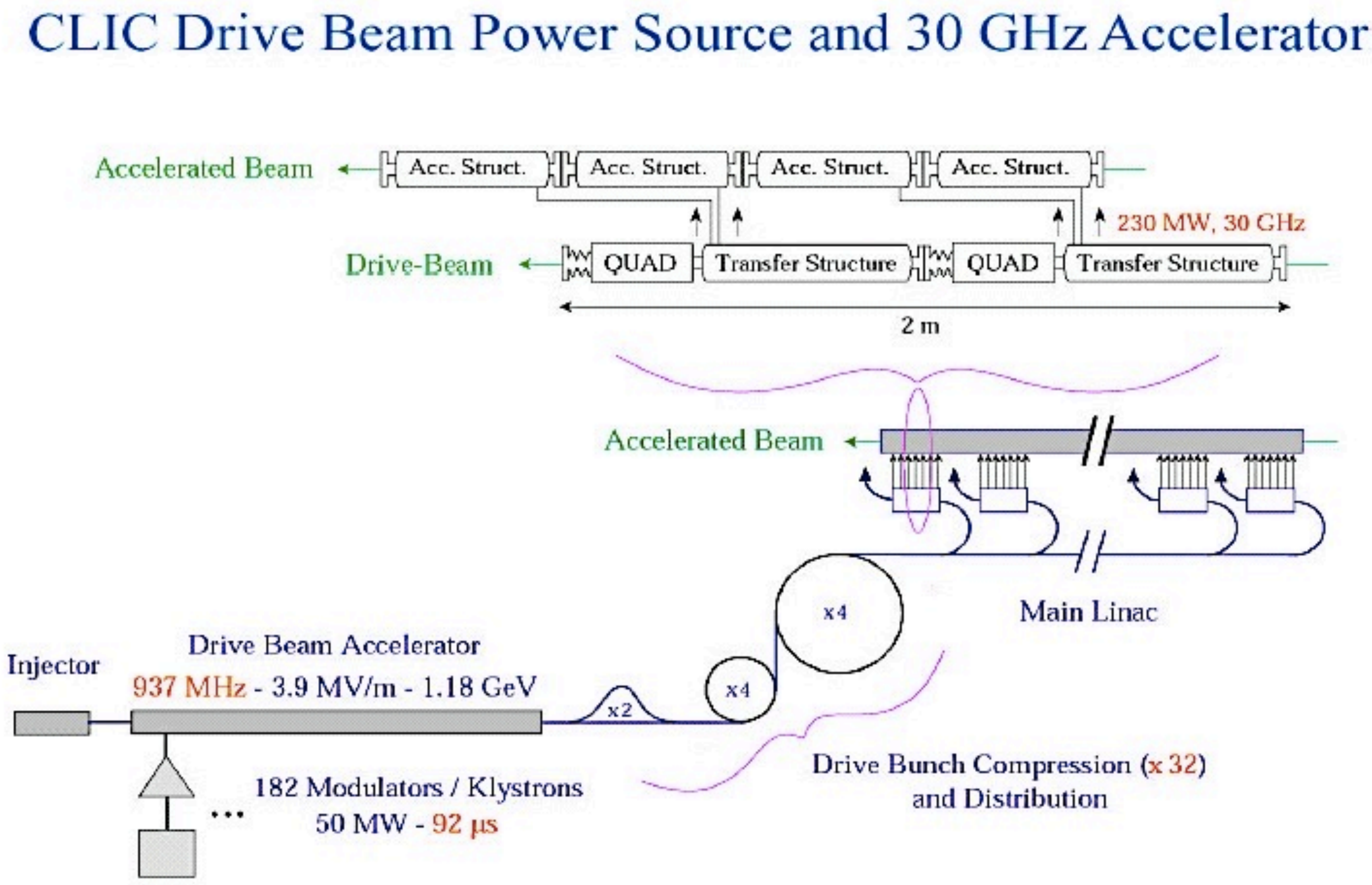
35 MV/m ~ 250 GV / 7 km



Yield in '08 ~ '09:
~ 70% @ 25 MV/m
~ 46% @ 35 MV/m

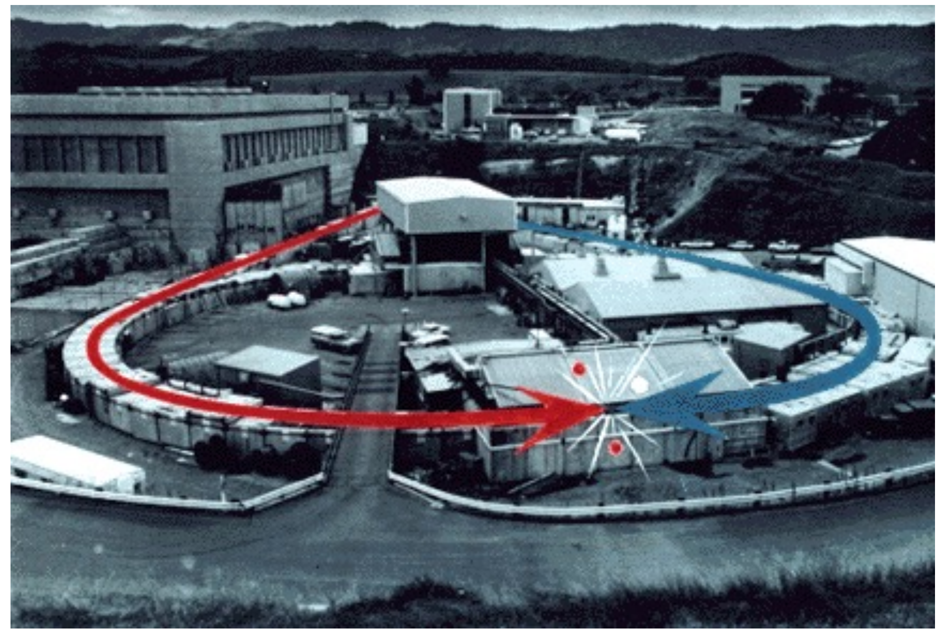
Yield in '10 ~ '12:
~ 85% @ 25 MV/m
~ 80% @ 28 MV/m
~ 70% @ 35 MV/m

CLIC (Compact Linear Collider)



Storage Ring

- SPEAR
  - completed in 1972
  - 80 meter diameter
  - E_{beam} up to 4 GeV
  - charm discovered in 1974
  - 1990 - dedicated to synchrotron radiation



The Largest Colliders

- Largest and highest energy colliders have been
  - Fermilab Tevatron (proton/antiproton with 1 TeV beam energy)
  - LEP II (electron/positron with 100 GeV beam energy)
  - Large Hadron Collider -LHC (proton colliding with 4 TeV beam now, going to 7 TeV beam energy)

Anti-proton Beam Cooling

- Proton/anti-proton colliders depended on beam cooling to achieve intense anti-proton beam (developed for SppS at CERN)

STOCHASTIC COOLING

- Sample particle's motion with pickup and correct motion with a kicker
- Cooling system works on individual (incoherent) particle amplitudes
- After a sufficiently long time (the cooling time) each particle is damped
- Every particle has a slightly different frequency of motion, and the force generated by all the other particles has a random phase that averages to zero.

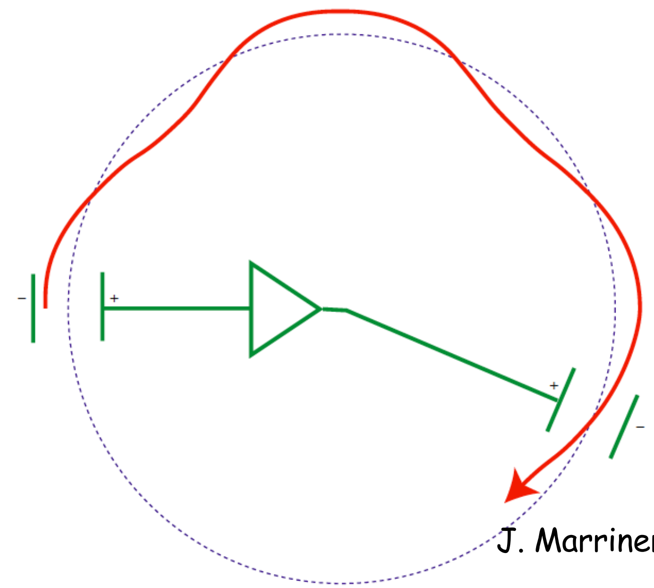


Figure 1. A cartoonist's view of a transverse stochastic cooling system.

- Net result is that cooling of each particle can be described by a damping force, which is created by the particle and is linear in the system feedback gain, and the heating force, which is created by all the other particles an averages to zero

Large Hadron Collider

- 14 GeV center-of-mass collisions
- Luminosity lifetime limited by:
  - beam lifetime limit due to interactions of the two beams at the IPs (-> total nuclear cross section)
  - beam size blowup due to intra-beam scattering
  - reduction in the beam intensity due to rest gas scattering
  - beam size reduction due to synchrotron radiation damping
  - beam size blowup due to the non-linear beam-beam interactions

Initial LHC Luminosity Lifetime

- Luminosity lifetime due to 2 high luminosity insertions (beam-beam interaction only; decay to 1/e of initial luminosity)
  - 84 h
- Vacuum beam lifetime
  - 100 h
- Horizontal intra-beam scattering(IBS) growth time at injection (without 200MHz RF)
  - 146 h
- Longitudinal IBS growth time at injection
  - 94 h
- Horizontal IBS growth time at 7 TeV
  - 300 h
- Longitudinal IBS growth time at 7 TeV
  - 180 h
- Total luminosity lifetime due to IBS, beam-beam, restgas [radiation damping neglected]
  - 28 h

Synchrotron Radiation

Radiation emitted by an electric charge travelling in a magnetic field, due to transverse acceleration. The total energy loss is given by

$$\mathrm{d}W/\mathrm{d}t = (2c/3)e^2\beta^4[E/(m_0c^2)]^4(1/r^2)\ ,$$

Consequently, the mean energy loss of electrons in a circular orbit due to synchrotron radiation is (per revolution)

$$W_r = t_r(\mathrm{d}W/\mathrm{d}t) = (4\pi/3)e^2\beta^3\gamma^4/r = CE^4/r$$

$$C = 8.85 \times 10^{-5} \quad [\mathrm{GeV}^{-3}/\mathrm{m}]\ .$$

Synchrotron radiation produces a broad energy spectrum at low energies;

above a *critical energy* $\epsilon_c = 3\hbar c\gamma^3/2r$ the falloff is exponential.

ε_c is also the median of the power distribution

LHC Synchrotron Radiation Effects

- S.R. Power deposition on cryogenic system
- Photon stimulated outgassing -> dynamic pressure increase
- Photoelectron production -> electron cloud effect
  - Power dissipation by bunched beam
  - Beam Induced Multipacting (BIM)
  - Electron stimulated outgassing
- Beneficial effects of S.R. :
  - Cleaning of the vacuum system (beam cleaning effect)
  - Reduction of secondary electron coefficient by photons/electrons
    (beam scrubbing)
  - For the VLHC : Radiation damping -> Increase of Luminosity

Comparison of S.R Characteristics

		LEP200	LHC	SSC	HERA	VLHC
Beam particle		e+ e-	p	p	p	p
Circumference	km	26.7	26.7	82.9	6.45	95
Beam energy	TeV	0.1	7	20	0.82	50
Beam current	A	0.006	0.54	0.072	0.05	0.125
Critical energy of SR	eV	$7\ 10^{5}$	44	284	0.34	3000
SR power (total)	kW	$1.7\ 10^{4}$	7.5	8.8	$3\ 10^{-4}$	800
Linear power density	W/m	882	0.22	0.14	$8\ 10^{-5}$	4
Desorbing photons	$s^{-1}\ m^{-1}$	$2.4\ 10^{16}$	$1\ 10^{17}$	$6.6\ 10^{15}$	none	$3\ 10^{16}$

Electron Synchrotrons

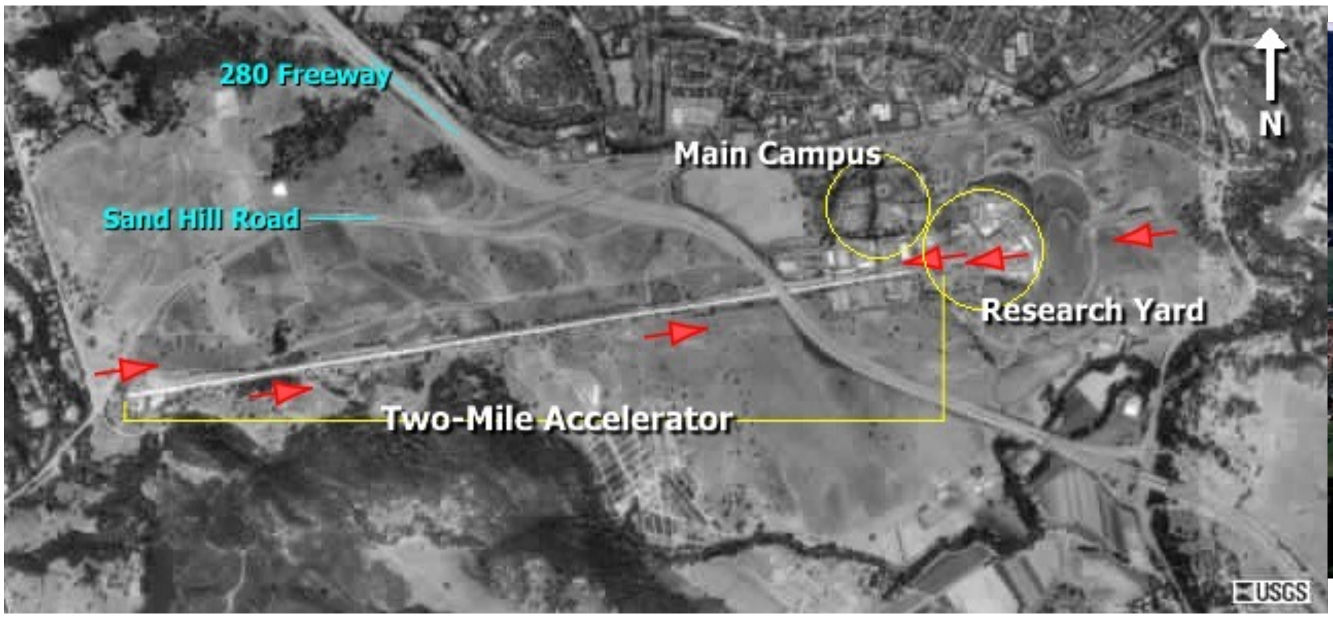
- Limited by growing synchrotron radiation
  - energy radiated per particle per turn

$$\Delta E = \frac{4\pi}{3}\left(\frac{e^2\beta^3\gamma^4}{\rho}\right)$$

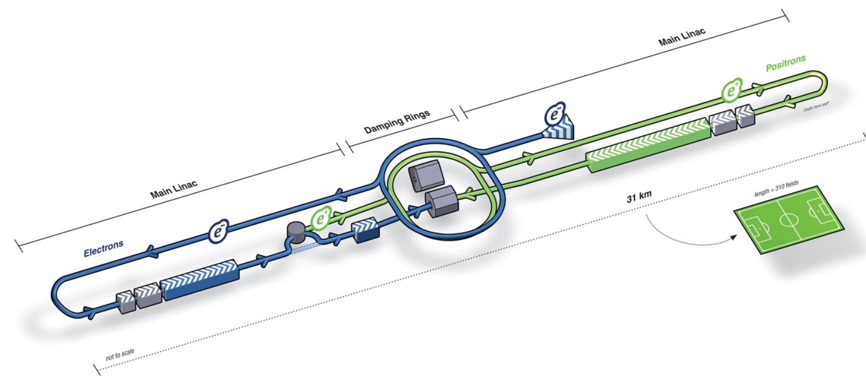
  - since energy loss scales as m^{-4}, radiation is $(M/m)^4 \approx 10^{13}$ times larger for electrons than protons
  - LEP (E_{beam} = 100 GeV) will be highest energy electron synchrotron
    - ΔE = 4 GeV
  - This effect motivated the large electron linac at SLAC in the 1960's

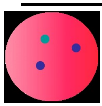
Electron Linear Accelerators

- SLAC was built for 25 GeV electrons with 240 klystrons
  - short 2 microsecond bursts of intense power at 60 Hz
  - eventually exceeded 50 GeV by shortening the pulse
    - also 120 Hz
- Avoids synchrotron radiation
- Loses advantage of multiple passes in circular accelerator



Standard Model Developed from Hadron and Lepton Collisions



SM particle	discovery	detailed study
	SLAC	HERA
	PETRA	Fermilab/ SLC/LEP
c	BNL SPEAR	SPEAR
τ	SPEAR	SPEAR
b	Fermilab	Cornell/DESY/SLAC/KEK
Z	SPPS/CERN	LEP and SLC
t	Fermilab	LHC +? (LC meas. Yukawa cp.)

Electron experiments frequently gave most precision as well as discovery

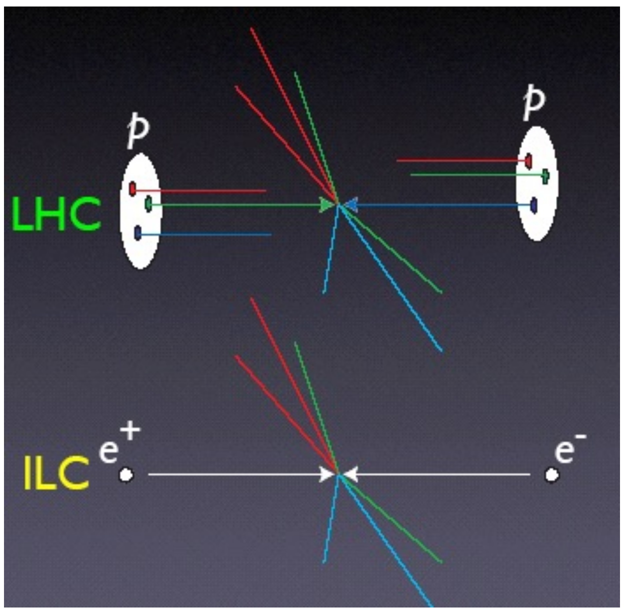
LESSON FOR THE FUTURE

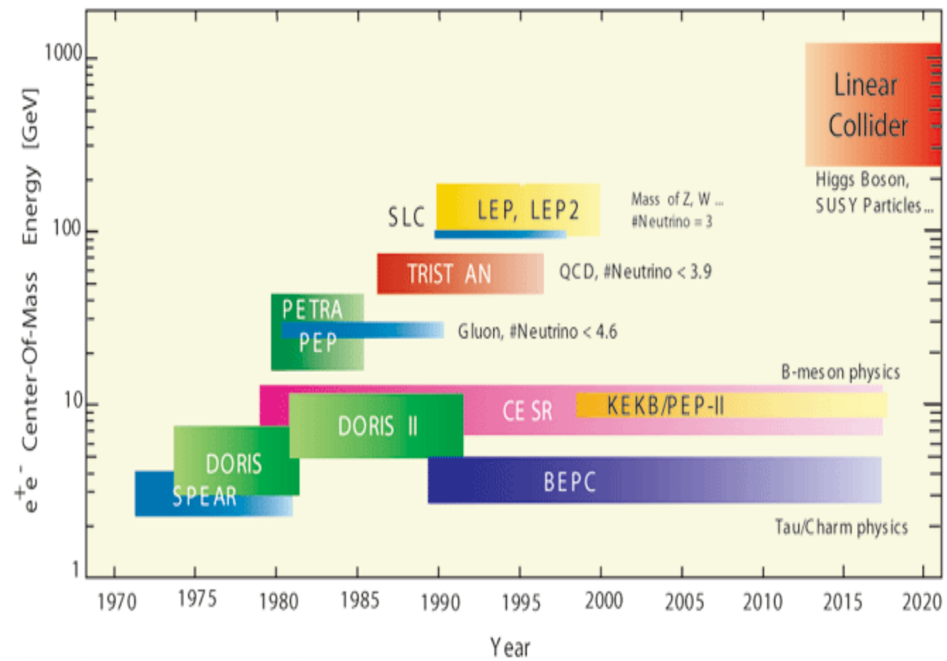
Complementarity of Lepton & Hadron Colliders

Astronomers examine the universe with different wavelengths
(visible, radio, X-ray, IR, etc.)

Particle Physics uses different initial states
for <u>independent</u> searches and tests

Such complementarity is a powerful tool across all sciences

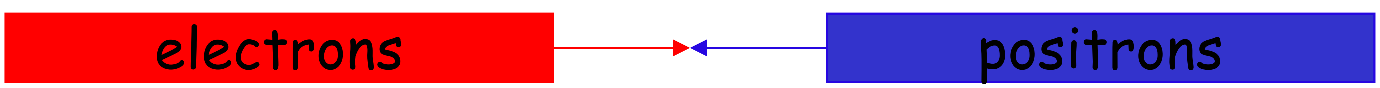


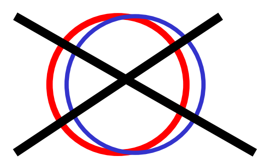


Linear Colliders

- Acceleration of electrons in a <u>circular</u> accelerator is plagued by Nature's resistance to acceleration
  - Synchrotron radiation
  - $\Delta E = 4\pi/3\ (e^2\beta^3\gamma^4 / \underline{R})$ per turn (recall $\gamma = E/m$, so $\Delta E \sim E^4/m^4$)
  - eg. LEP2 $\Delta E = 4$ GeV Power ~ 20 MW

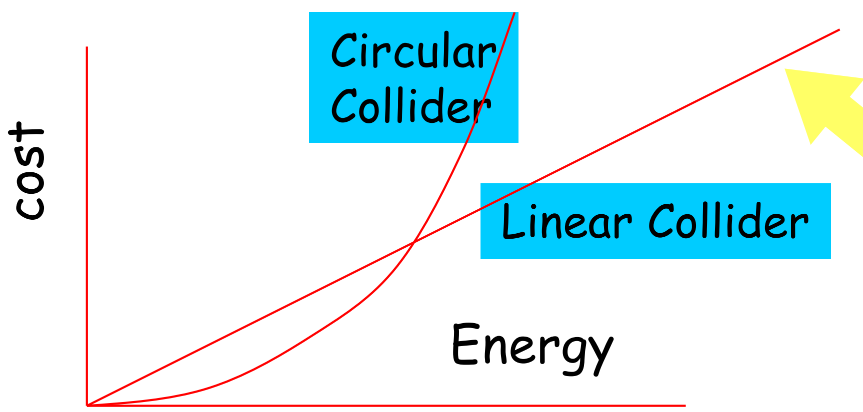
- For this reason, at very high energy it is preferable to accelerate electrons in a <u>linear</u> accelerator, rather than a circular accelerator





Linear Colliders

- Synchrotron radiation
  - $\Delta E \sim (E^4 / m^4 R)$
- Therefore
  - Cost (circular) $\sim a R + b \Delta E \sim a R + b (E^4 / m^4 R)$
    - Optimization $R \sim E^2 \Rightarrow$ Cost $\sim c E^2$
  - Cost (linear) $\sim a' L$, where $L \sim E$

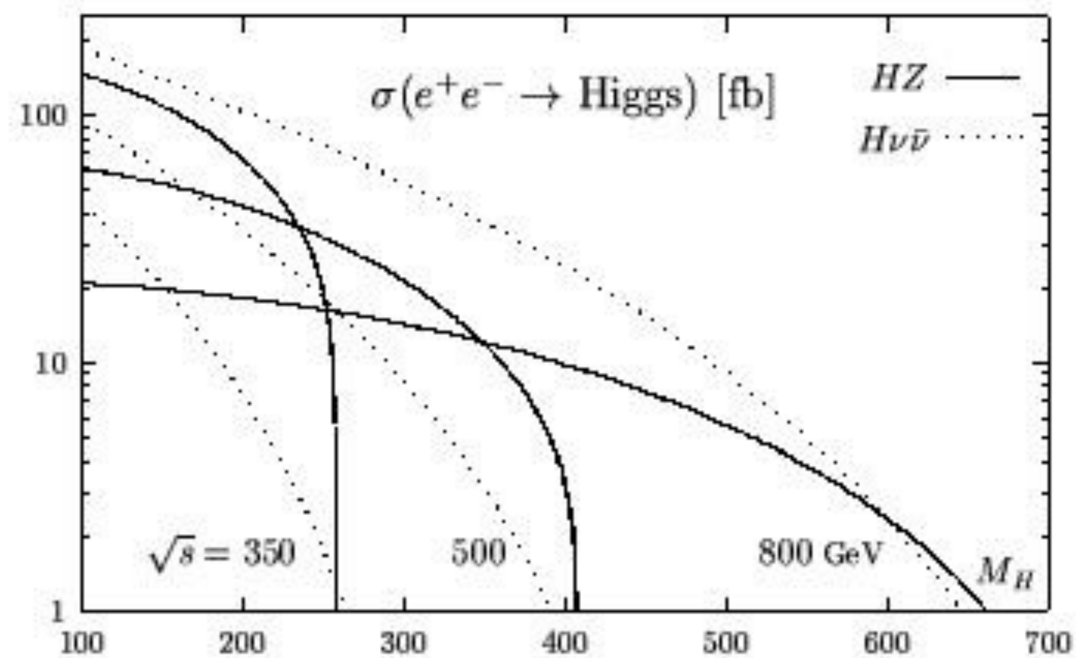


- At high energy, linear collider is more cost effective

Linear Colliders

- The First Linear Collider
  - SLAC Linear Collider (SLC)

- "next" Linear Collider
  - ILC (0.5 – 1 TeV)
  - CLIC (0.5 – 3 TeV)

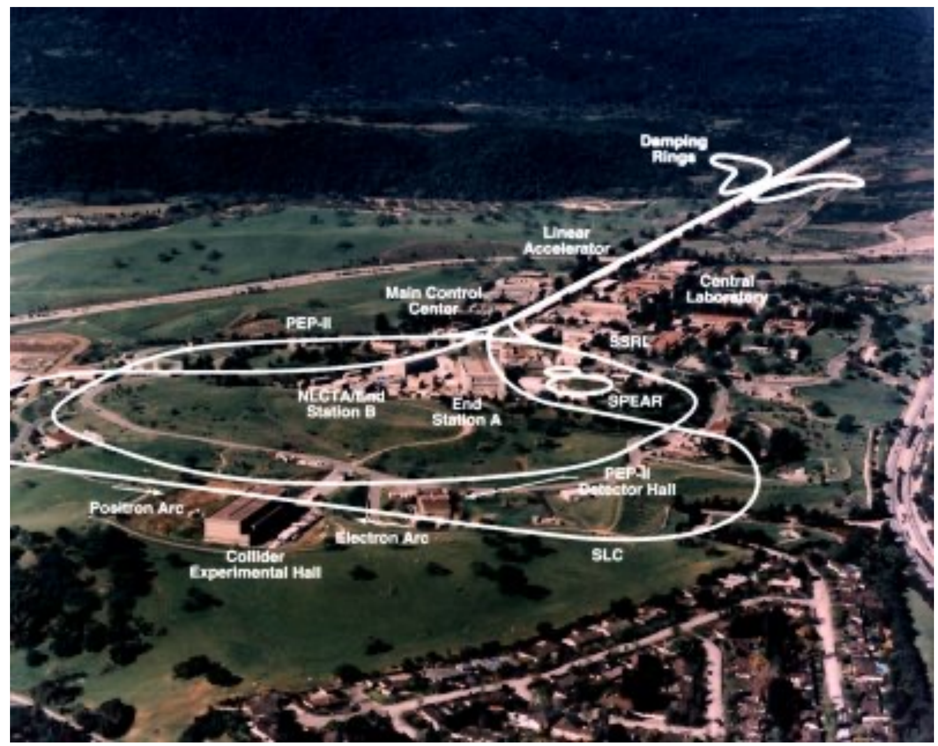


The First Linear Collider (The SLC)

- This concept was demonstrated at SLAC (Stanford Linear Accelerator Center) in a linear collider prototype operating at ~91 GeV (the SLC)

- SLC was built in the 80's within the existing SLAC linear accelerator

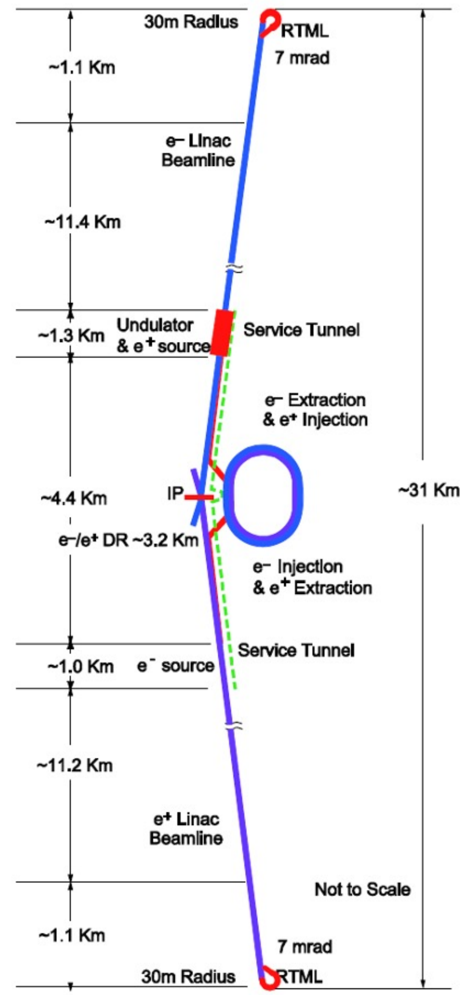
- Operated 1989-98
  - precision Z^0 measurements
  - established LC concepts



The International Linear Collider (ILC)

- A plan for a high-energy, high-luminosity, electron-positron collider (international project)
  - E_{cm} = 500 - 1000 GeV

- Physics Motivation for the ILC
  - Elucidate Electroweak Interaction
    - particularly symmetry breaking
    - including searches/studies of
      - Higgs bosons
      - supersymmetric particles
      - extra dimensions
      - other new particles and interactions



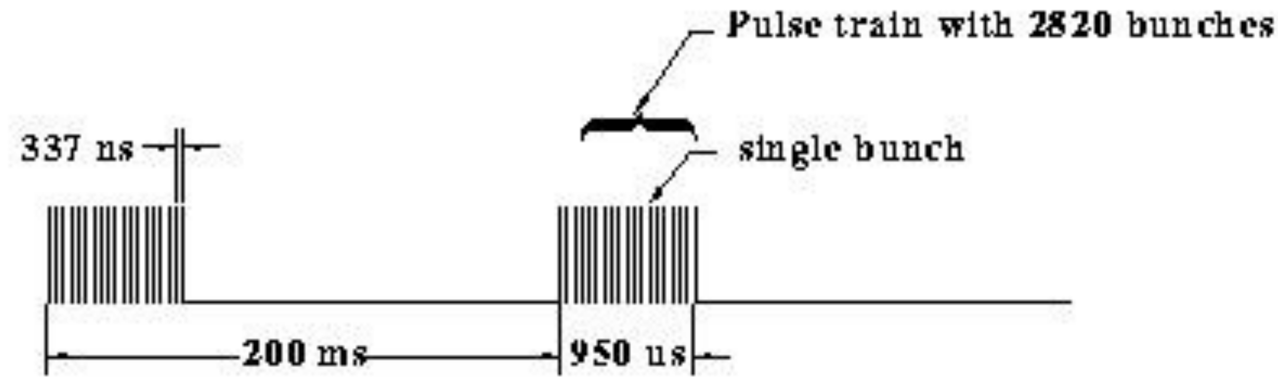
not to scale

ILC

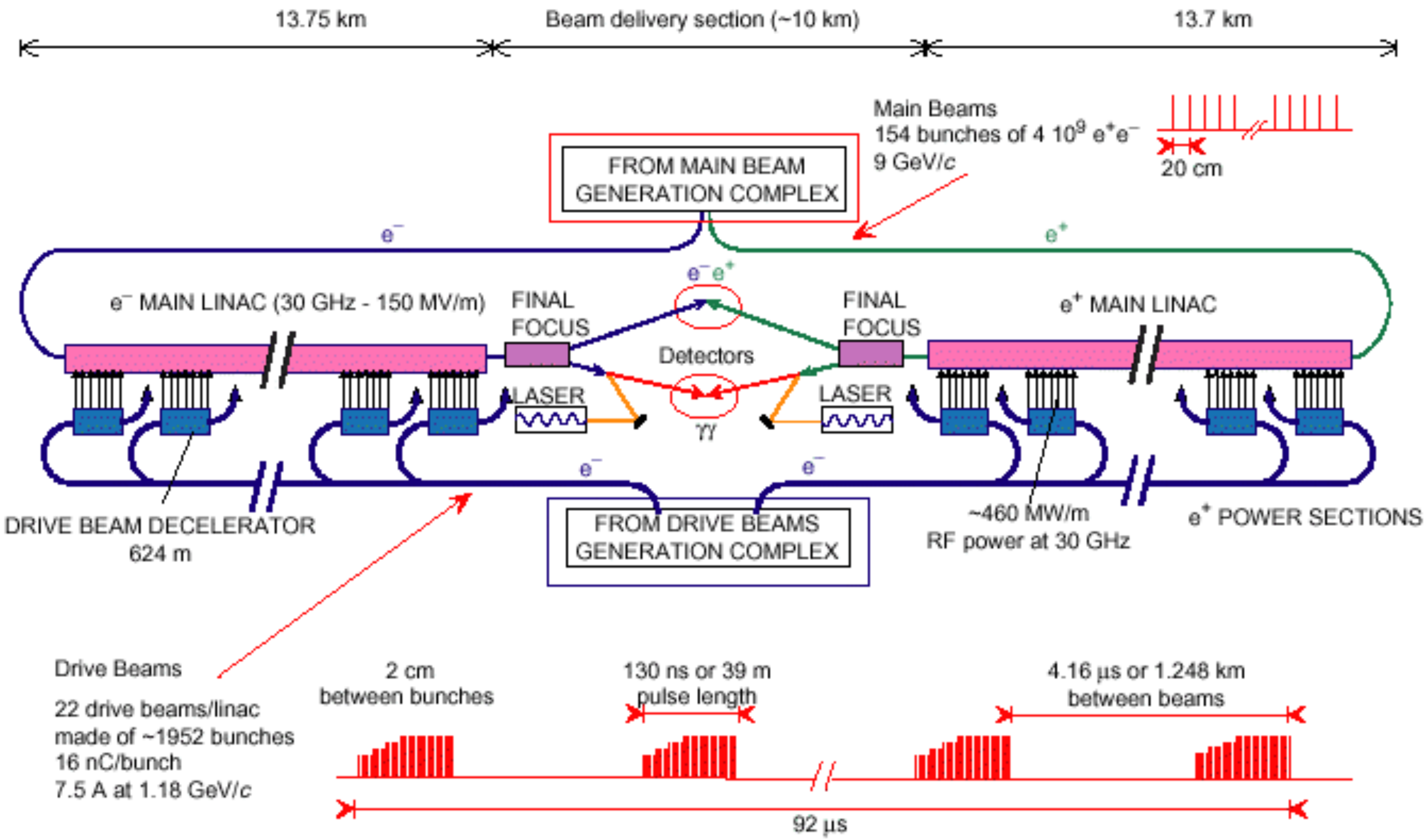
- Superconducting RF
- Low temperature

TESLA 9-cell cavity

Time Structure



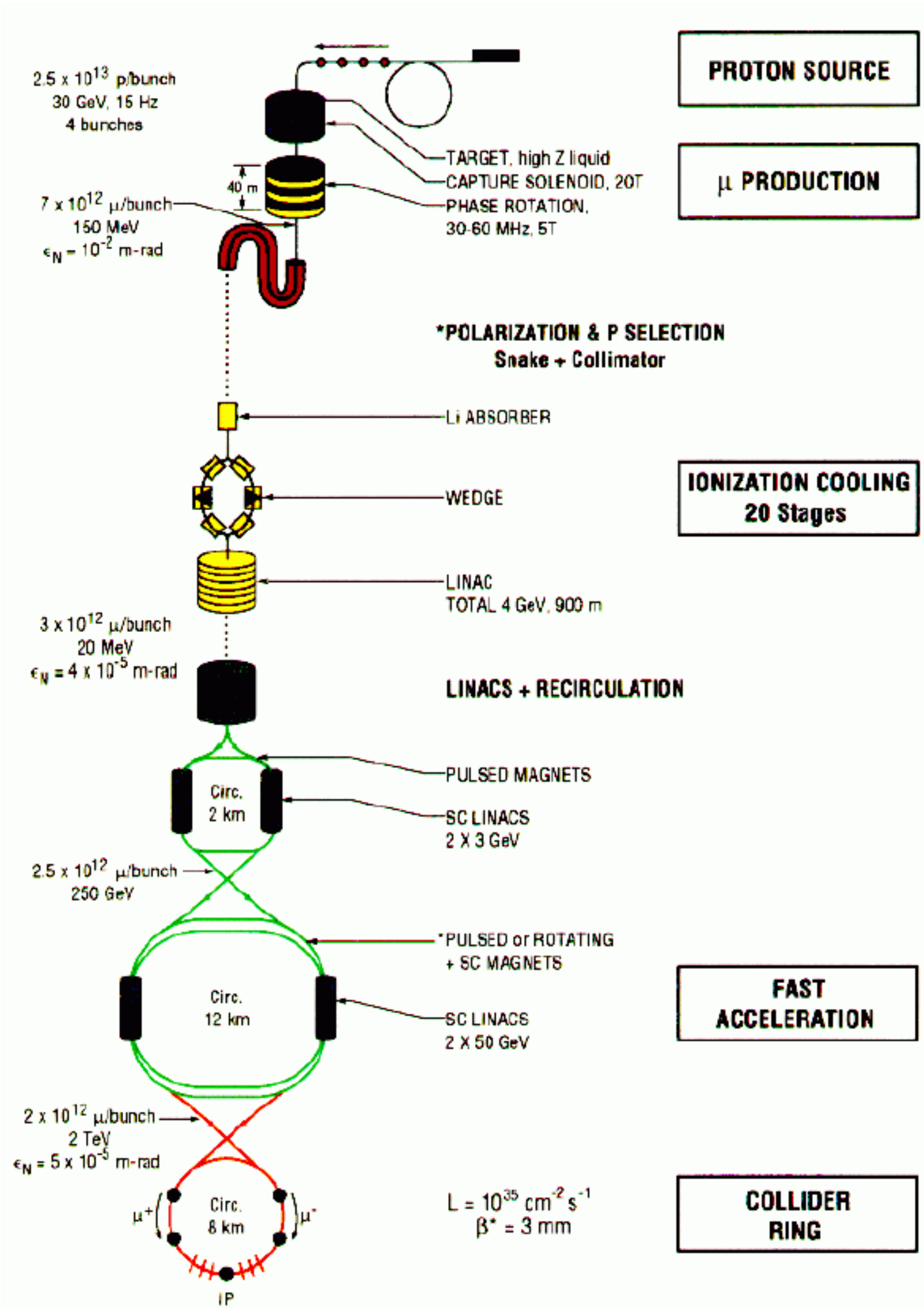
CLIC (Compact Linear Collider)



Muon Collider

- Motivation: electron collider limited at high energy
  - length of linear collider -> \$
  - beamstrahlung - limits L - but $\sigma \sim 1/s$ so need $L \sim s$
  - muons can be stored in a circular machine
- Problems for Muons
  - unstable 2×10^{-6} secs -> $\gamma c\tau \sim 6 \times 10^{2}\,\gamma$ meters
  - produced as large beam -> need to focus
- Higgs Factory
  - coupling to Higgs $\sim m_f^2$ 4×10^4 x electron

Muon Collider



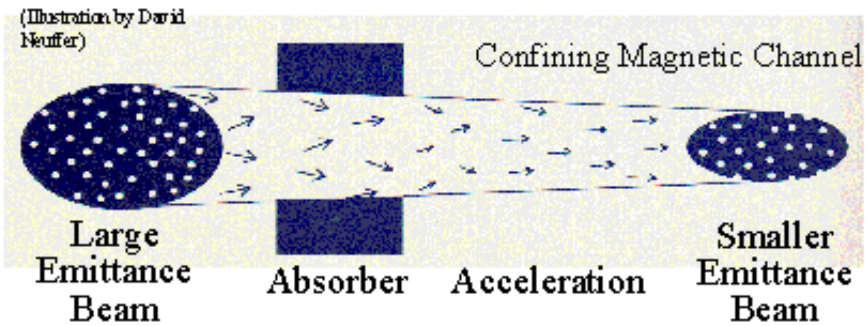
Muon Collider

- Ionization Beam Cooling
- Neutrino Radiation
- Detector Radiation
- The Future
  - first step - neutrino factory
    - demonstrates storage and cooling

IONIZATION BEAM COOLING

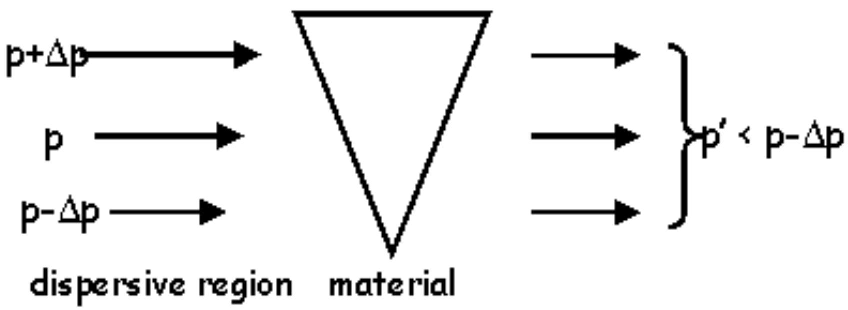
Need factor of ~10^6 in 6-D cooling ≡ reduction of rel. invariant 6-D phase space volume: $\varepsilon_{6N} \equiv \prod_{i=x,y,z} \Delta p_i \Delta x_i$

Transverse Cooling



The cooling channel is the biggest technical challenge common to all muon colliders.

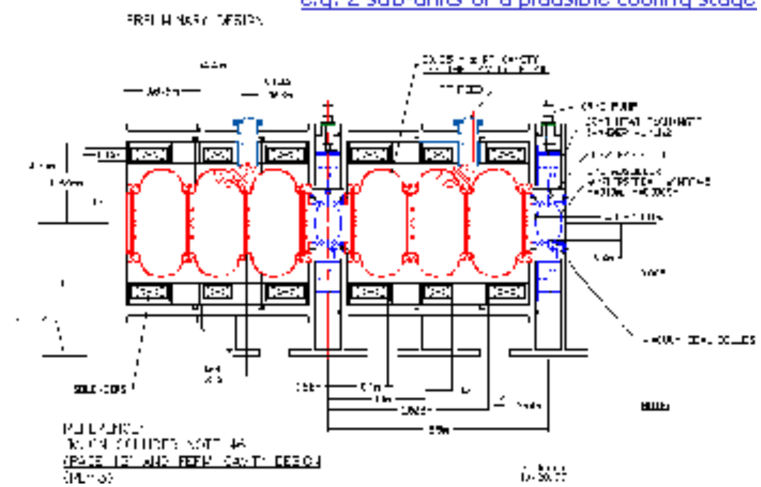
Longitudinal Cooling (ΔEΔt) => "Emittance Exchange



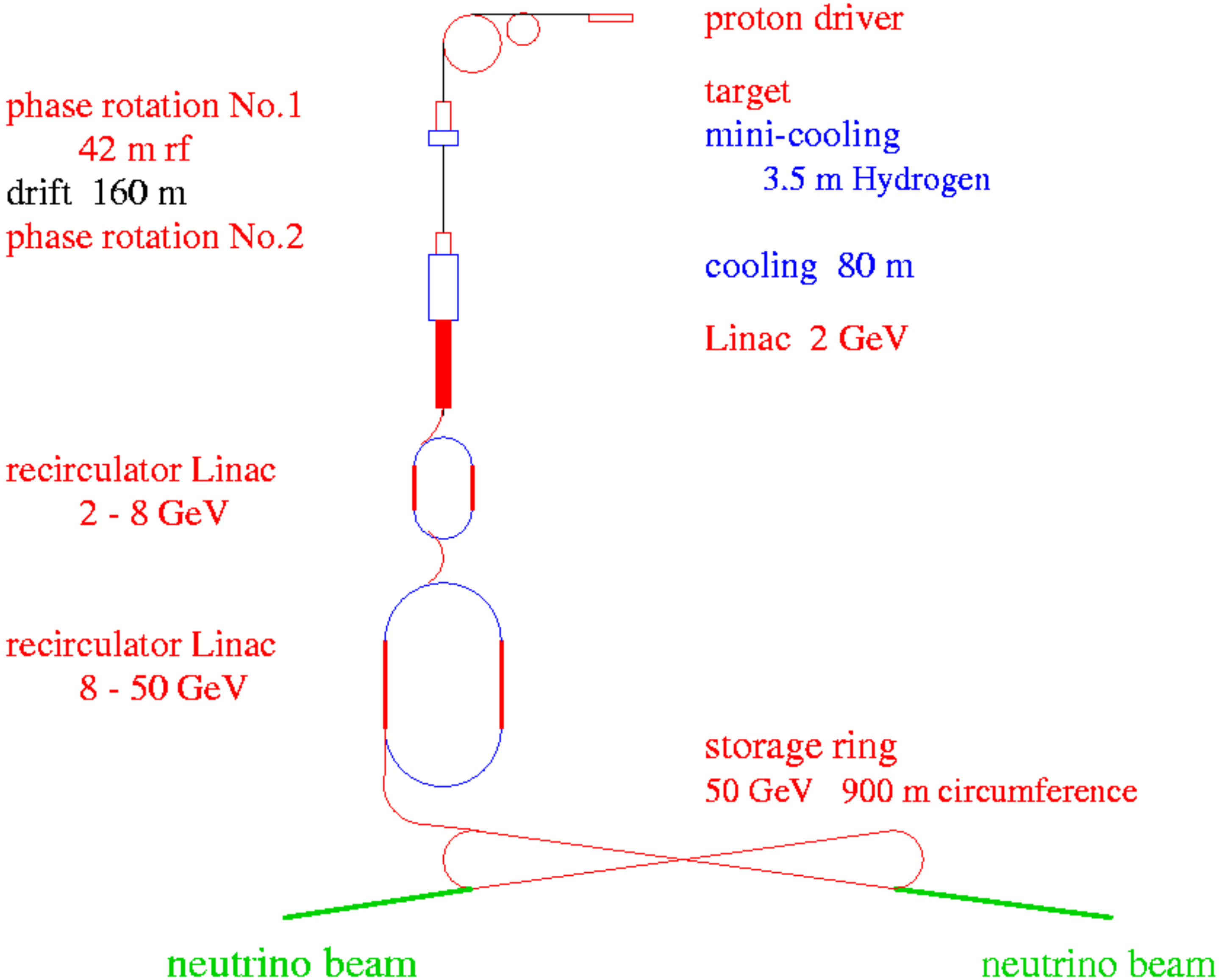
NEW: encouraging simulations of fully 6-D cooling channel in ring geometry; ref. V. Balbekov, Muon Collider Note 189, http://www-mucool.fnal.gov

The Cooling Channel Will be Novel and Complex

e.g. 2 sub-units of a plausible cooling stage



Neutrino Factory



VLHC

- 30 TeV x 30 TeV
  - since LHC = 7 TeV x 7 TeV = 14 TeV
    - 8.4 T -> 27 km circumference
- Options for 30 TeV x 30 TeV
  - low field, large ring
    - 1.8 Tesla -> 388 km circumference
  - high field, small ring
    - 13 Tesla -> 60 km circumference

Dugan

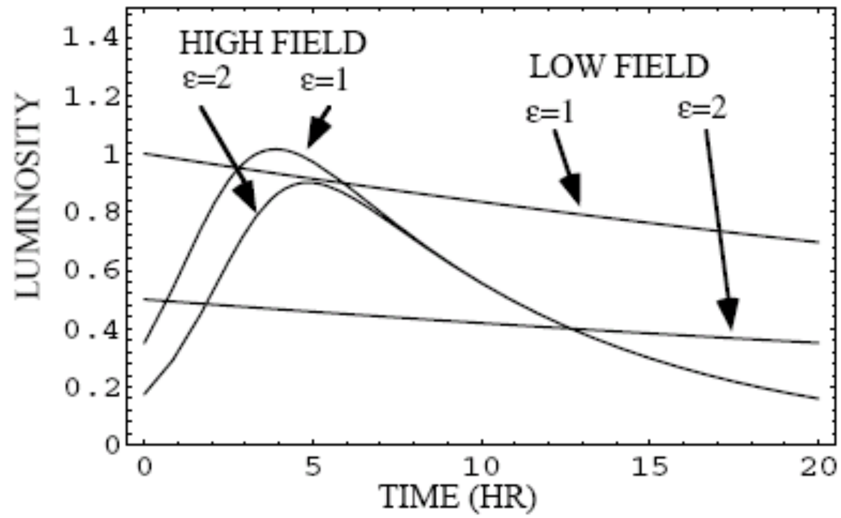


FIG. 2: Time evolution of the luminosity (in $10^{34}\text{cm}^{-2}\text{sec}^{-1}$). Emittances are given in π µm-rad.

Synchrotron Radiation Facilities

- A broad spectrum of science has benefited from the development of large storage rings for high energy physics
  - source of synchrotron radiation
  - initially parasitic operation from HEP facilities
  - dedicated facilities
  - future plans, such as LCLS