Particle Accelerators

Physics 290E, Spring 2025

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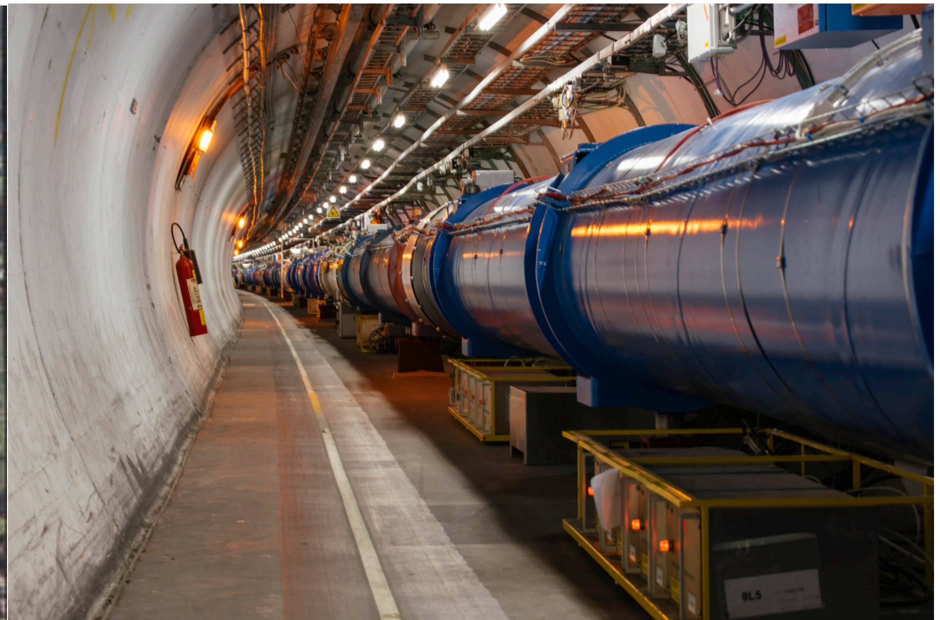
Jan 29, 2025





Why Accelerators ?

- "A better magnifying glass"
  - Need to look deeper into the structure of matter
  - Spatial resolution is limited by wavelength of the probe
    - ☞ Microscope: visible light $\lambda \sim 1\ \mu m \rightarrow$ cell structure
    - ☞ Higher energy particles: $\lambda = 2\pi/p$
    - ☞ X-rays: $\lambda \sim 0.01\text{–}10$ nm $\rightarrow$ atomic, crystal structure
  - Charged particles:
    - ☞ Rutherford experiment: $p \sim 10$ keV, $\lambda \sim 10^{-10}$ m
    - ☞ Discovery of quarks: $p \sim 10$ GeV, $\lambda \sim 0.1$ fm
    - ☞ LHC: $p \sim 1\text{–}10$ TeV, $\lambda \sim 10^{-16}\text{–}10^{-17}$ m $\rightarrow$ quark structure, compact extra dimensions,

New Particles

- Most elementary particles are unstable (WIMPs not seen yet ☺) → create them in high-energy collisions
  - Energy conservation needs no explanation ☺
- Most recent:
  - c quark (J/Ψ meson): SLAC/SPEAR (3-7 GeV c.m. energy) and BNL (28 GeV protons on Be target)
  - b quark (Υ(1S) meson): FNAL (400 GeV pN fixed target)
  - t quark: FNAL (1.8 GeV c.m. $p\bar{p}$ collisions)
  - τ lepton: SLAC/SPEAR
  - W/Z bosons: CERN/SppS: 540 GeV c.m. $p\bar{p}$ collisions
  - Higgs boson: CERN/LHC: 12-14 TeV c.m. pp collisions

Fixed Target vs Collider

- Energy reach
  - What is relevant for high-energy collisions is CM energy of the fundamental process
  - Colliding beams (assuming E >> m):

$$E_{cm} \approx \sqrt{4E_1E_2}$$

  - Fixed (stationary) target:

$$E_{cm} \approx \sqrt{2m_tE_b}$$

- Other advantages of collider beams
  - Re-circulating beams possible
  - Collisions between fundamental particles
- Advantages of fixed target facilities
  - High event rates (see next)
  - Variety of targets and beams (including beams of unstable particles)
  - Boost for secondaries (this may be a disadvantage too !)

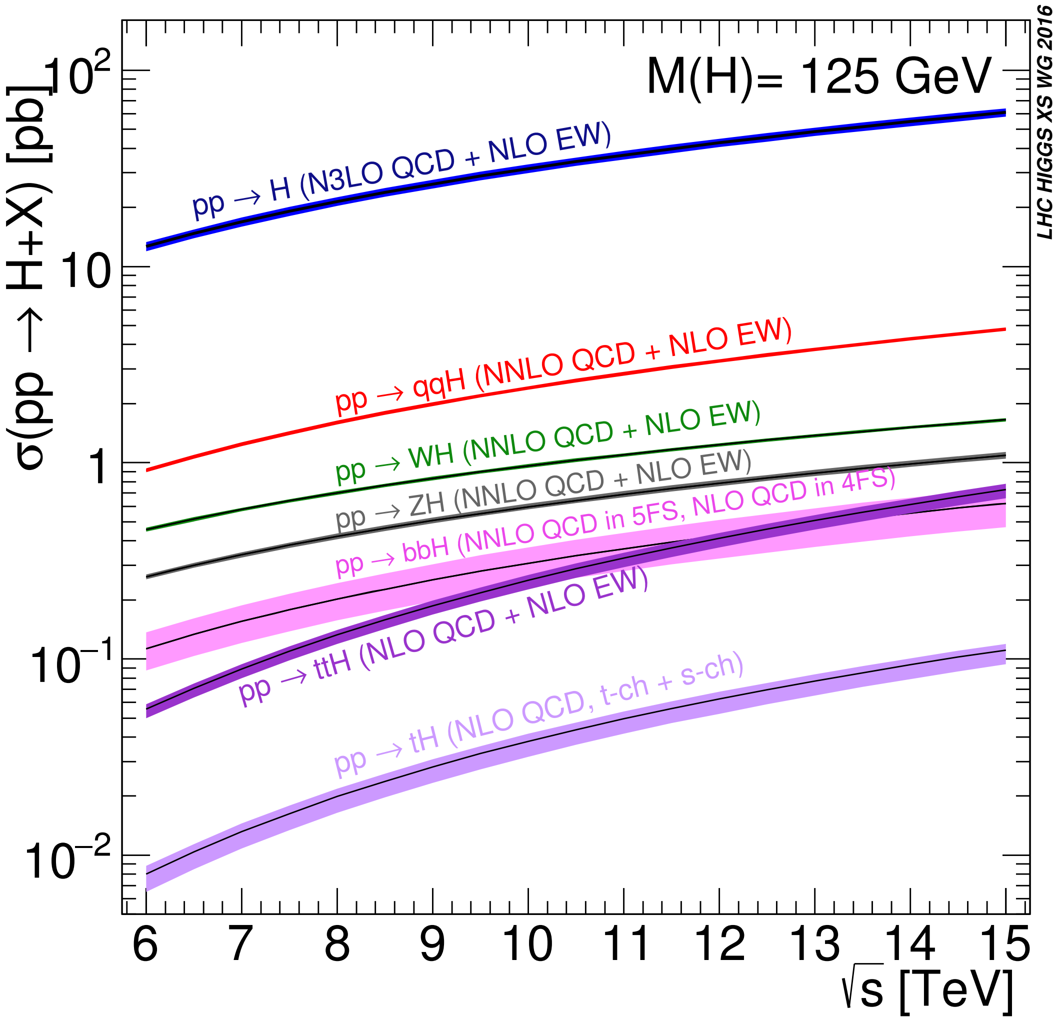
Event Rates

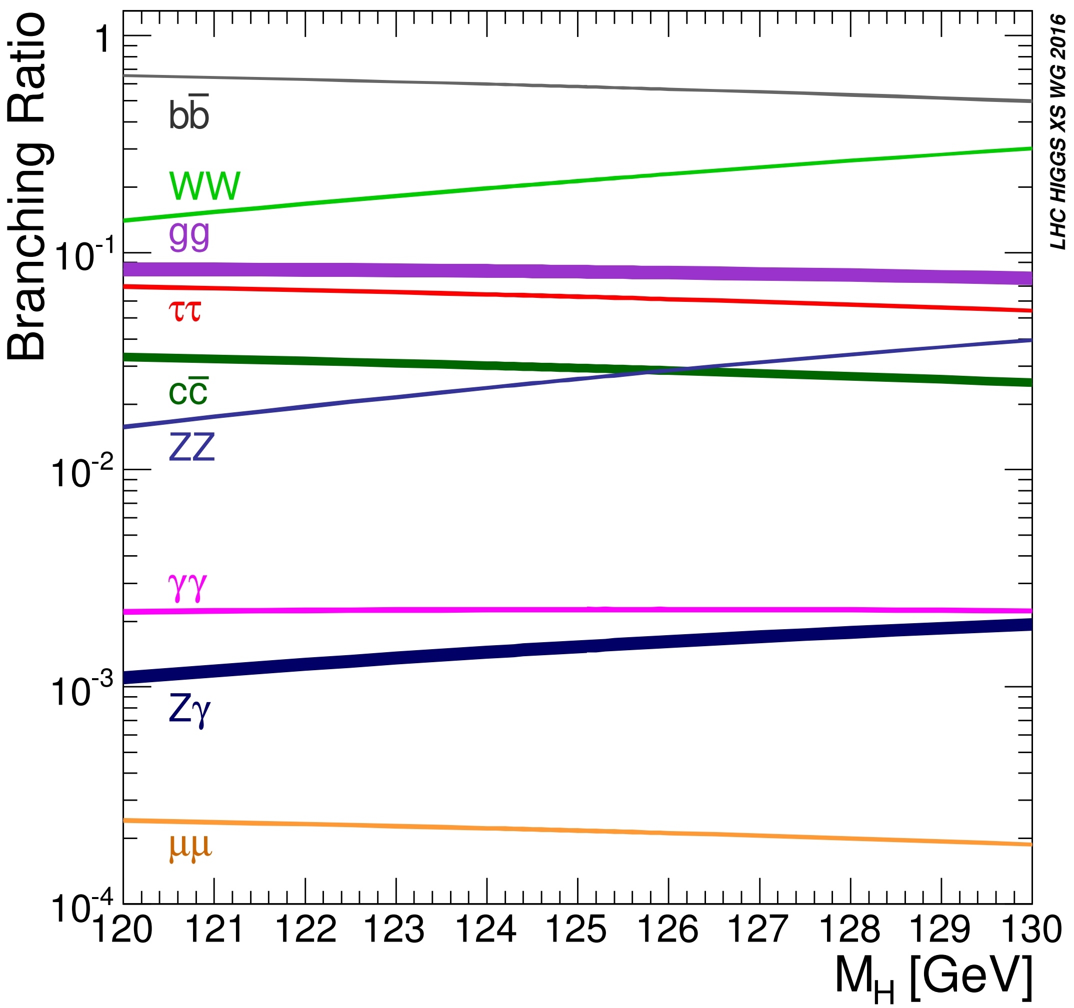
- Colliders:
  - $R = \sigma\mathcal{L}$: $\mathcal{L}$ is *instantaneous* luminosity [$cm^{-2}s^{-1}$ or $fb^{-1}year^{-1}$]
  - For colliders

$$\mathcal{L} = fn\frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

  - Here f is revolution frequency, n is number of bunches in a ring, N_i is # of particles in the bunch, and σ is the beam size
- Typical luminosities:
  - FNAL: 10^{31}–10^{32} $cm^{-2}s^{-1}$ (10-100 $\mu b^{-1}s^{-1}$, 0.1-1 $fb^{-1}year^{-1}$)
  - LEP,SLC: ~10^{31} $cm^{-2}s^{-1}$ (10 $\mu b^{-1}s^{-1}$, 0.1 $fb^{-1}year^{-1}$)
  - PEP-II, KEKB: 10^{34} $cm^{-2}s^{-1}$ (10 $nb^{-1}s^{-1}$, 100 $fb^{-1}year^{-1}$)
  - HL-LHC: 5×10^{34} $cm^{-2}s^{-1}$ (50 $nb^{-1}s^{-1}$, 500 $fb^{-1}year^{-1}$)

Event Rates


M(H)= 125 GeV
LHC HIGGS XS WG 2016
σ(pp → H+X) [pb]
pp → H (N3LO QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD + NLO EW)
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → ttH (NLO QCD + NLO EW)
pp → tH (NLO QCD, t-ch + s-ch)
√s [TeV]


Branching Ratio
LHC HIGGS XS WG 2016
bb̄
WW
gg
ττ
cc̄
ZZ
γγ
Zγ
μμ
M_H [GeV]

Fixed Target Event Rates

$$R = \sigma N_b n_t L$$

Beam rate (→ N_b)

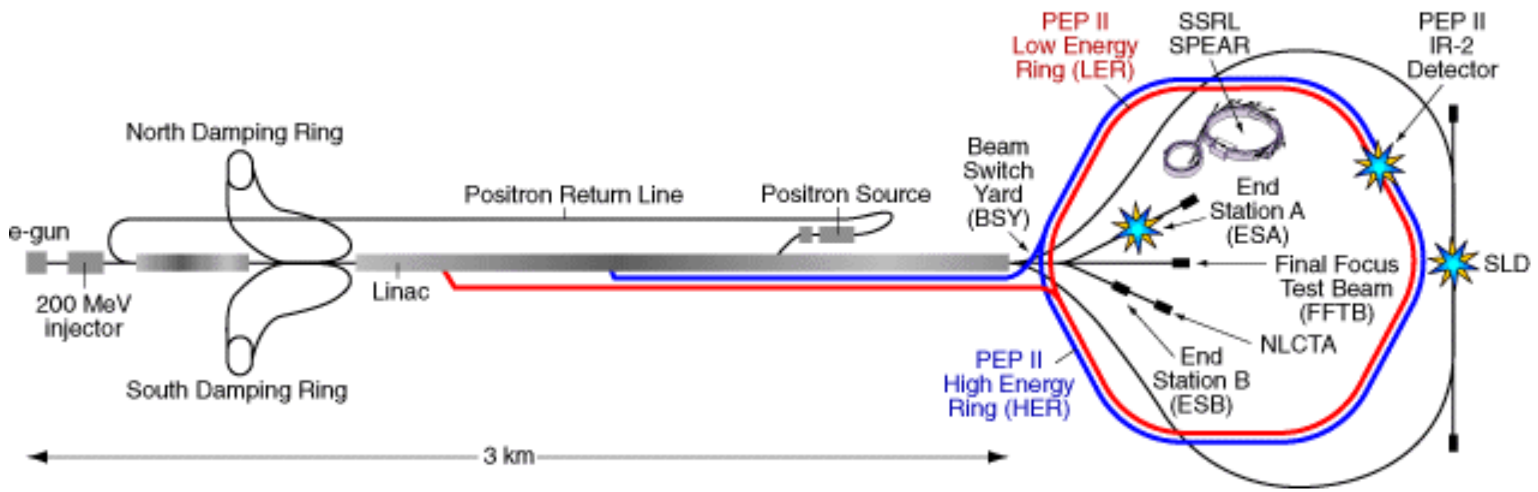
Target number density, $n_t = \rho / m_0$ (→ n_t)

Target length (→ L)

- Much higher rates achievable with modest beam currents and sizes
  - For example, a 1m liquid hydrogen target and a beam of 10^{13} particles per second are equivalent to ~10^{38} cm^{-2}s^{-1} luminosity
  - ☞ Example from E158 at SLAC

Components of an Accelerator

- Particle source
- Damping systems (reduce beam size)
- Particle acceleration
- Beam delivery systems (to fixed-target or collider regions)
- Beam dump



Particle sources

- Electrons
  - Thermal
  - Photo-electric
  - Polarized
- (Heavy) ions including protons
  - ECR sources
- Indirect (secondary beams)
  - High energy photons
  - Positrons
  - Neutrons
  - Muons, pions, kaons

Thermionic Gun

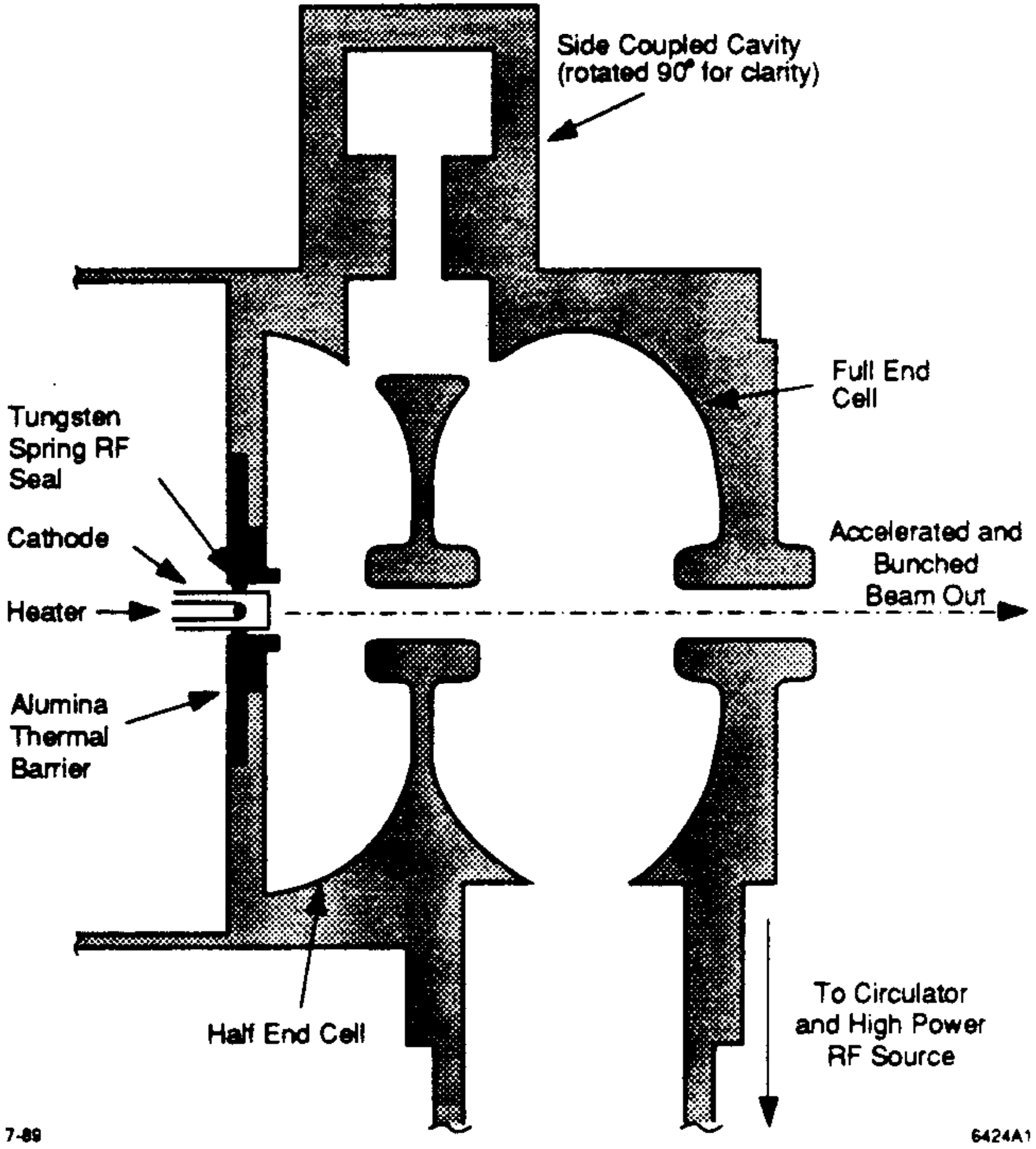
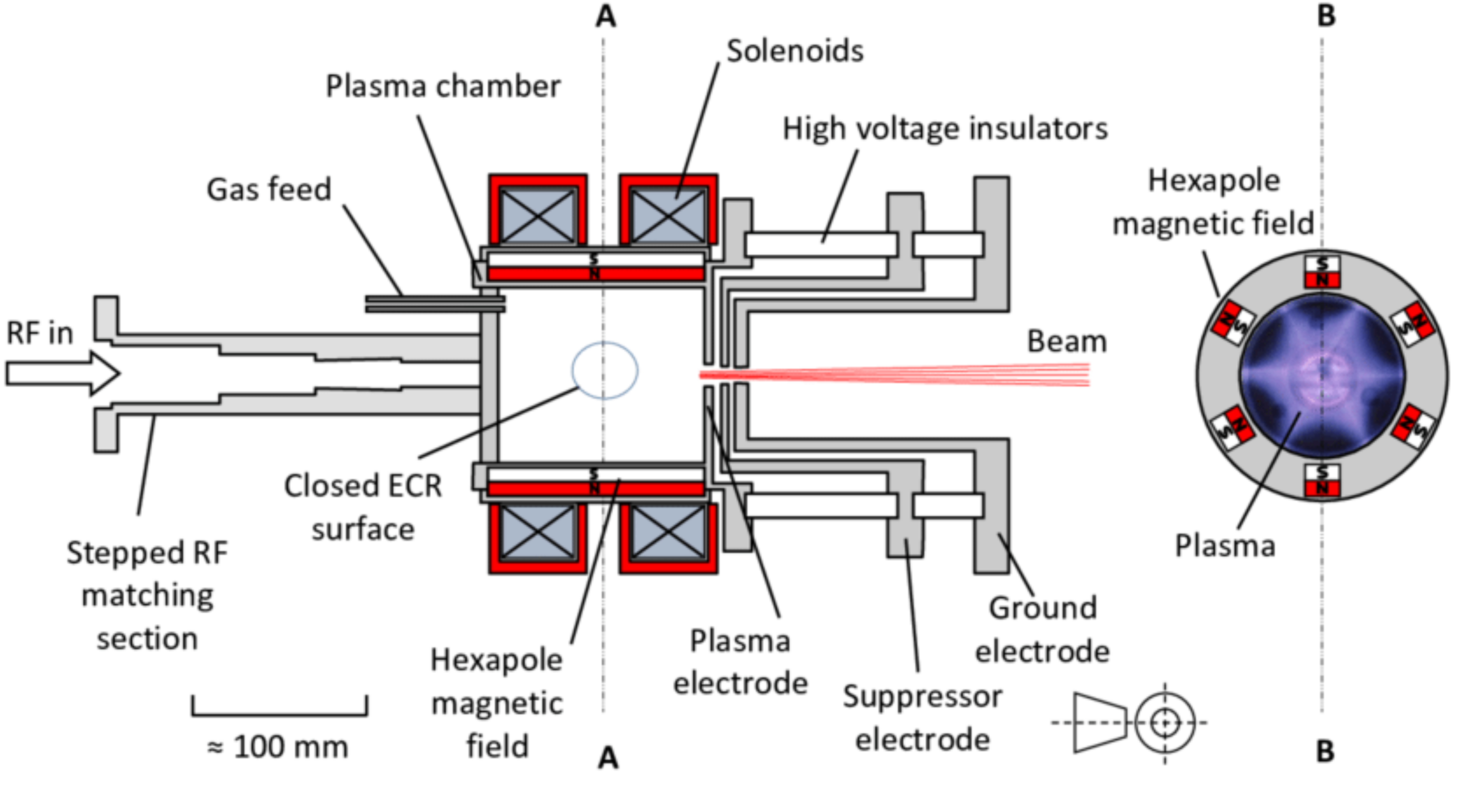


Fig. 1: Cross-sectional view of the 1-1/2 on-axis cells.

ECR Source

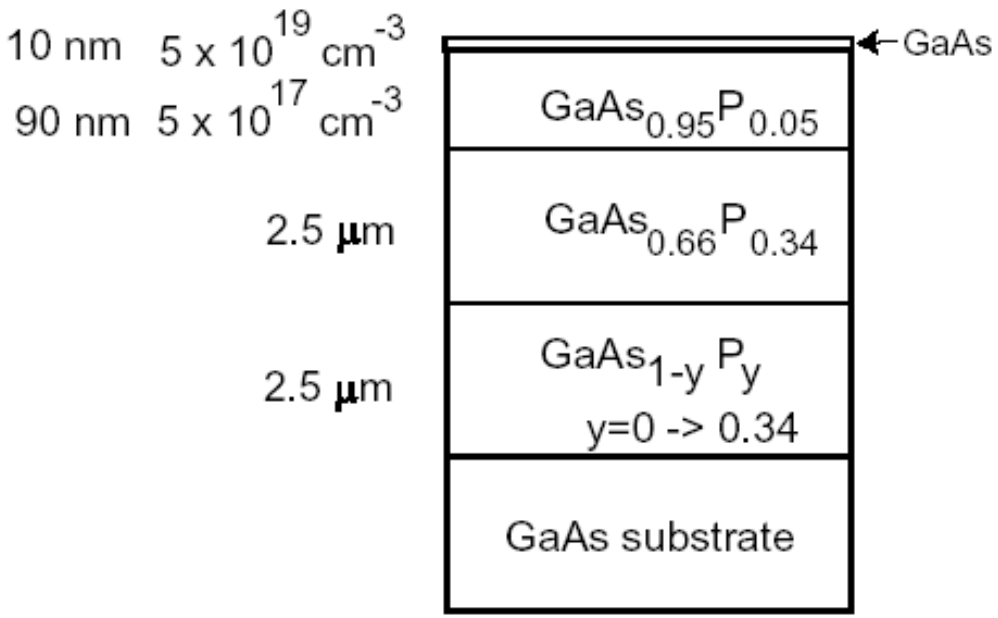
- Electron Cyclotron Resonance



Polarization

- Spin is the basic quantum number
- Electroweak couplings are helicity-specific
- Access to polarized beams and/or targets provides additional degree of freedom
    - Precision electroweak studies of couplings
    - Precision studies of nucleon structure
- Polarized sources:
    - Semiconductor photocathodes (electrons)
    - Sokolov-Ternov effect (electrons/positrons)
    - Secondary production (positrons, protons)
    - Electron or laser cooling (protons)
- Polarized targets
    - Optical pumping
    - Dynamic nuclear polarization

Polarized Source Photocathode



Reference: T. Maruyama et al., SLAC-PUB-9133, March 2002; (submitted to Nucl. Inst. Meth. A)

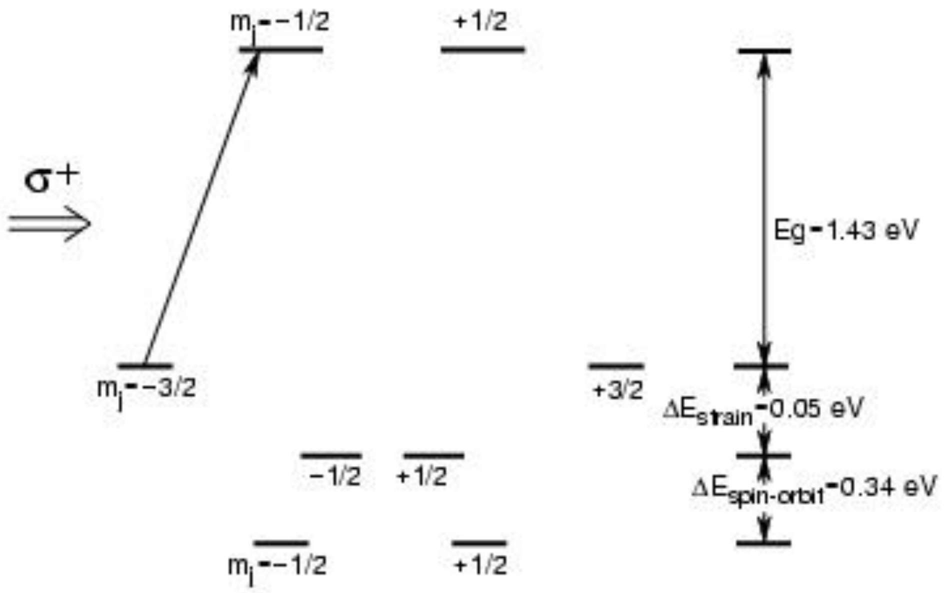
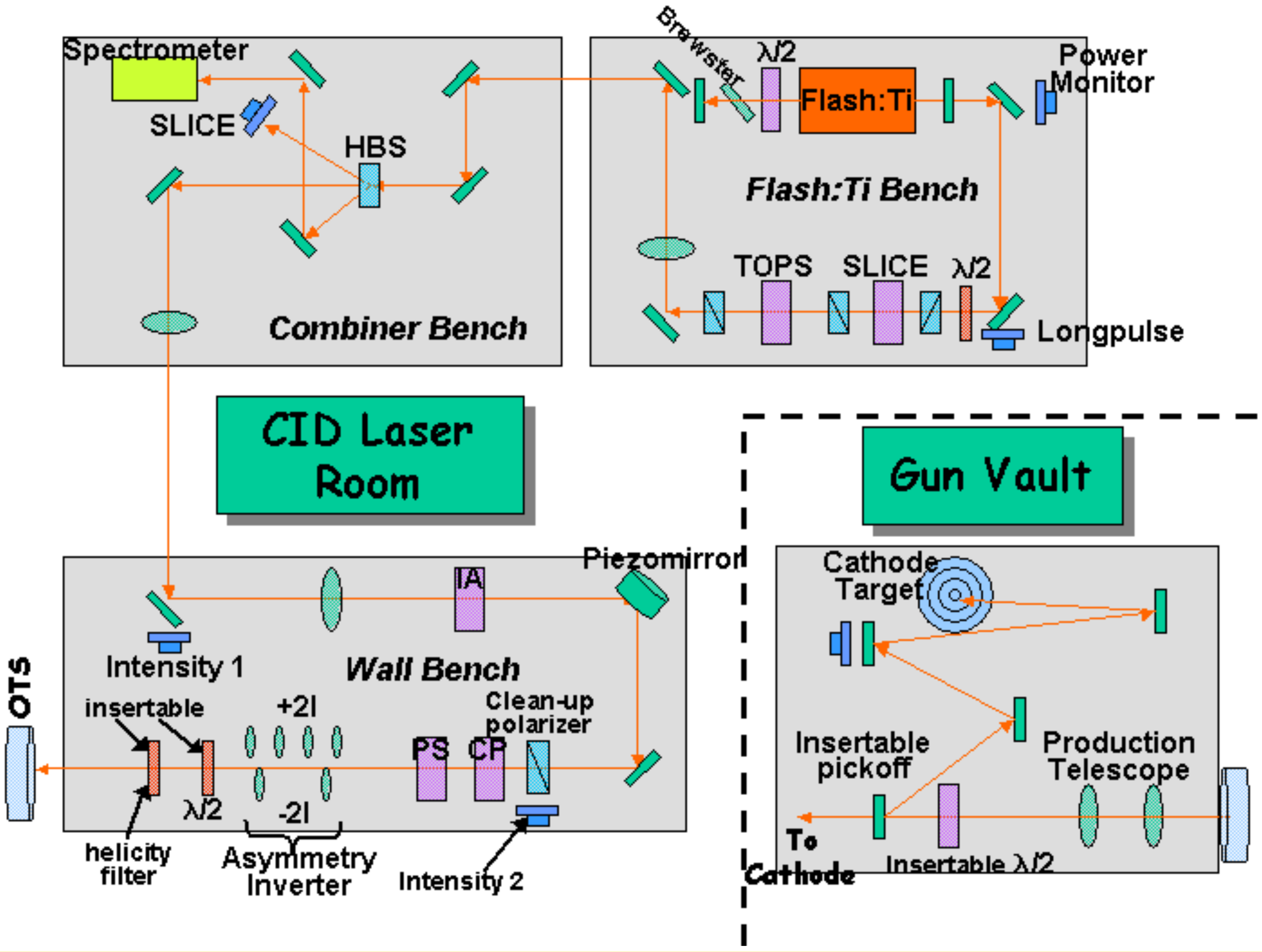


Fig. 2.2. Energy levels in strained GaAs.

NOTES:

1. High polarization (>80%) and available charge (~10^{11} electrons/pulse)
2. Non-strained cathodes: limit 50% polarization
3. Small anisotropy in strain: ~3% analyzing power for residual linear polarization

Polarized Laser System

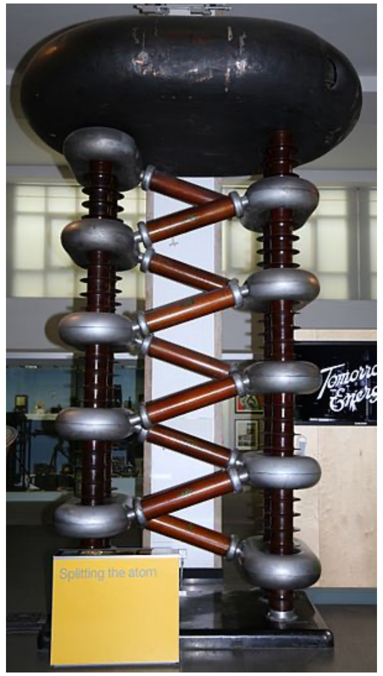


Particle Acceleration

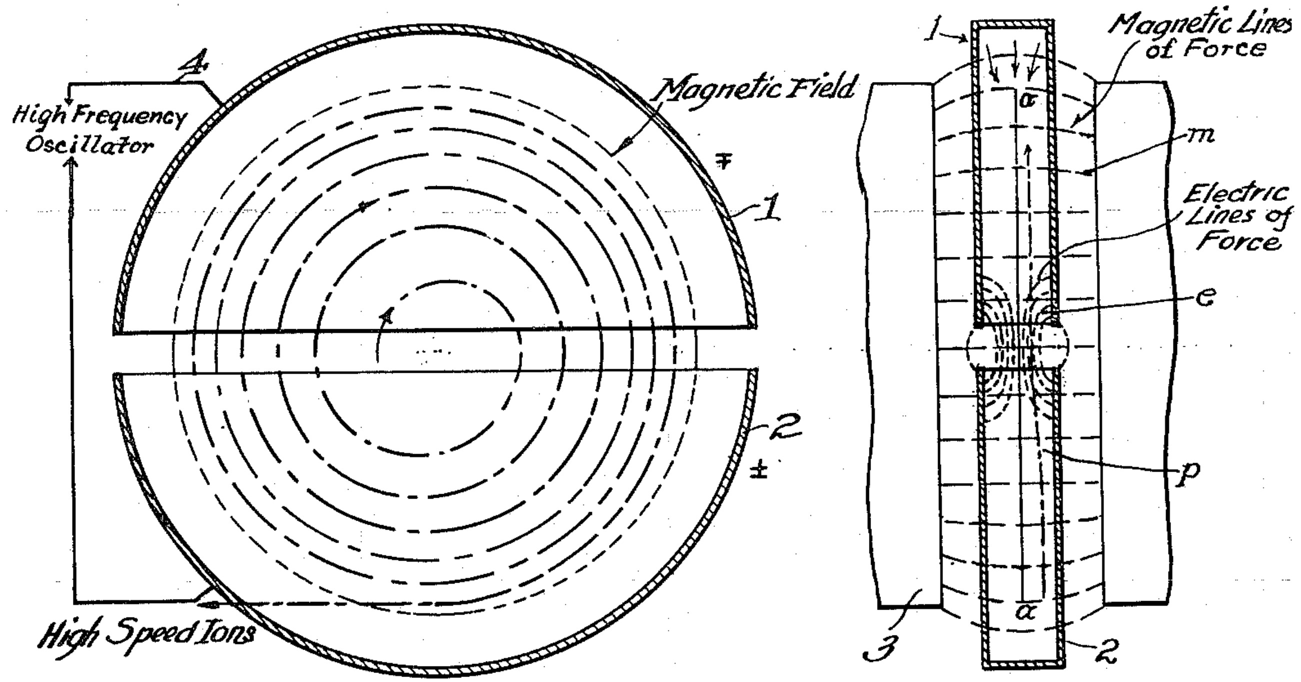
- Physics depends on CM Energy
- Use Electric (EM) fields to accelerate charged particles
  - $\Delta E = V e$
- Non-relativistic
  - Static (or slowly-varying) E fields
  - <100 kV/m, limited by corona
- Relativistic
  - Dynamic fields
  - >10 MV/m, limited by breakdown of conductor

Low-energy Accelerators

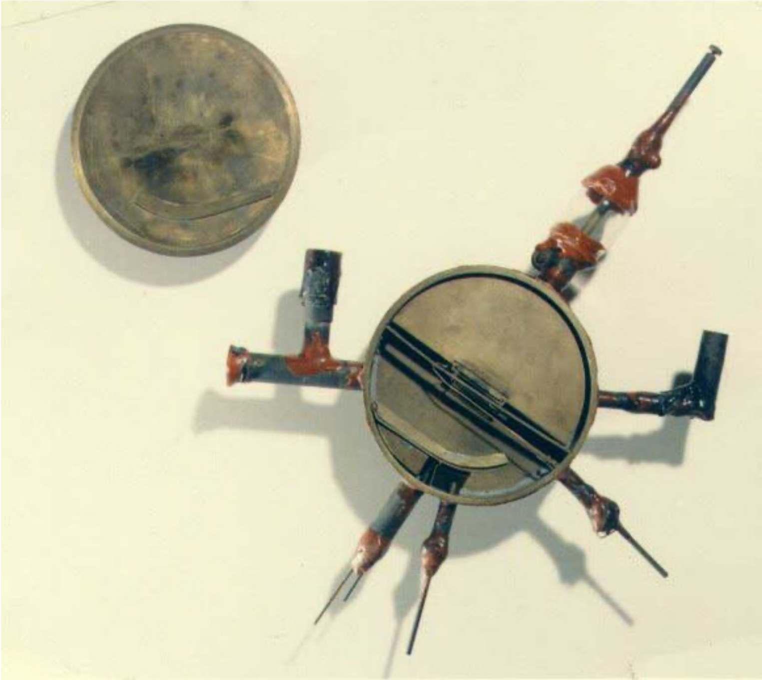
- Static E-field
  - Vandergraaf
  - Crockroft-Walton



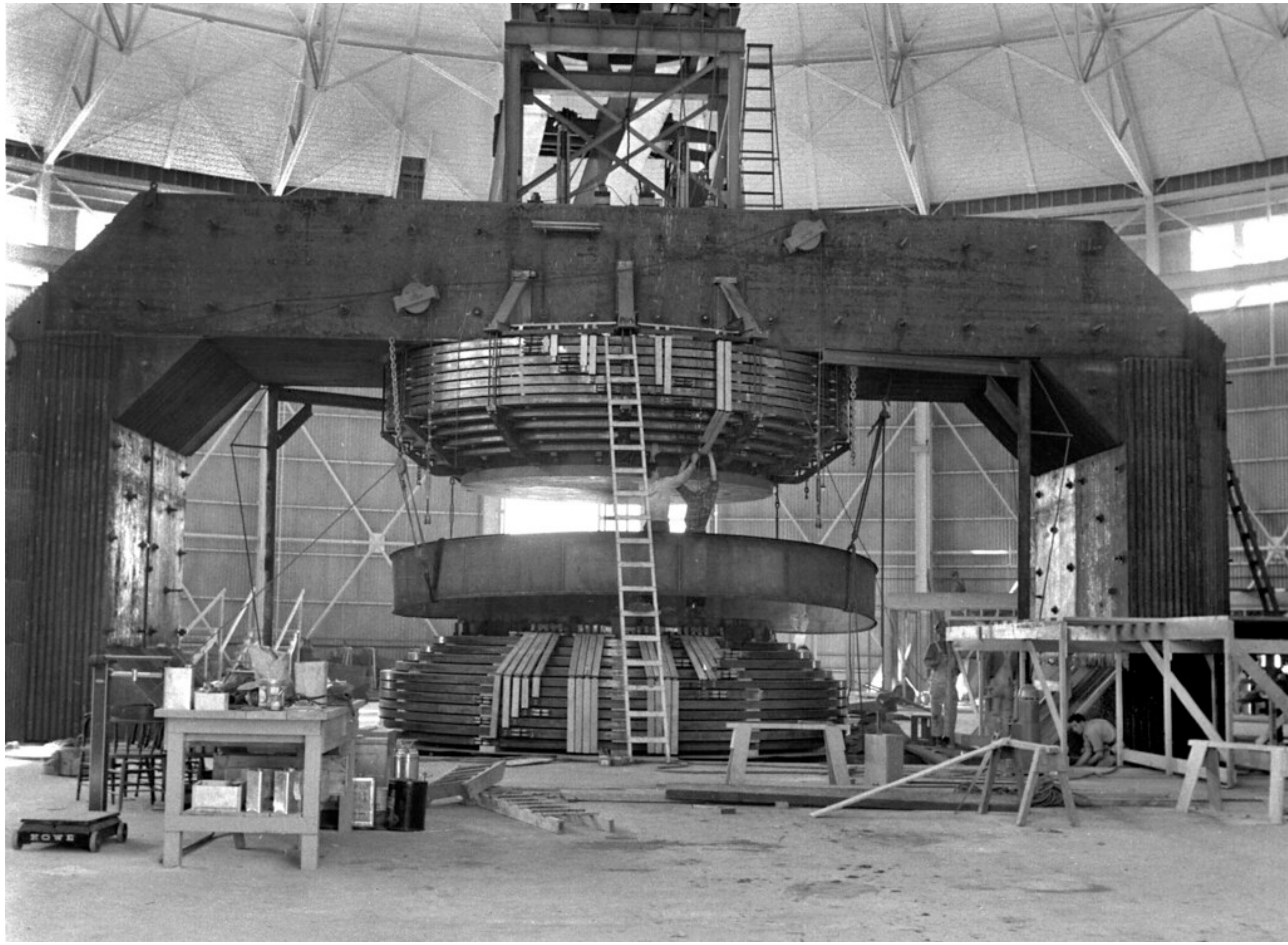
- Cyclotron
  - Static B field, variable E-field



Cyclotrons



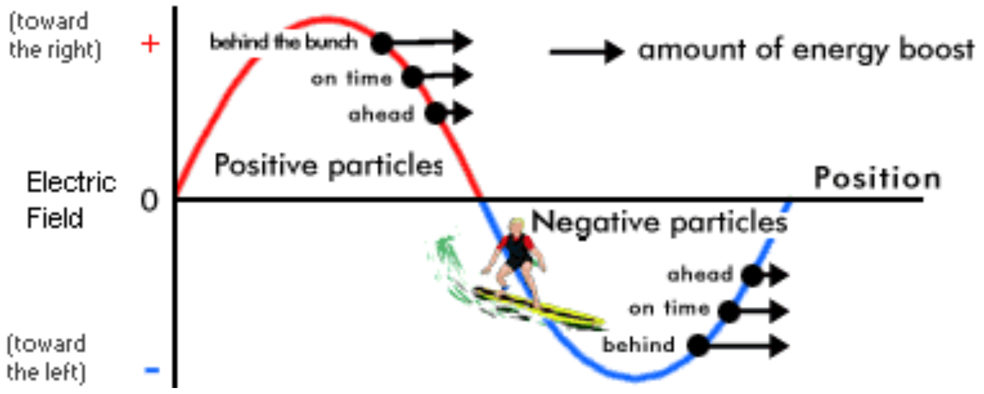
Lawrence's
4.5" cyclotron

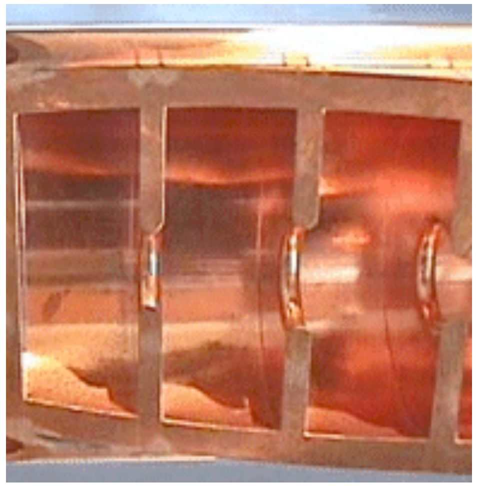


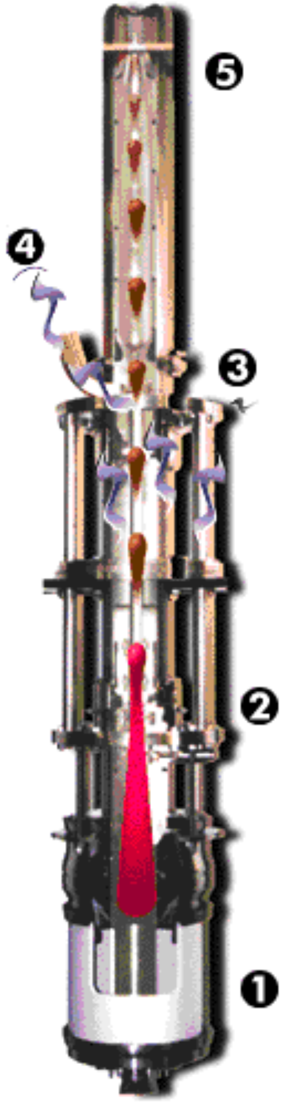
184" cyclotron

RF Acceleration

- Electrons are accelerated in alternating electric field form in a series of cavities
  - SLAC cells are copper with length of ~1/3λ at frequency 2856 MHz
  - NLC/CLIC design used X band cavities at f=11.4 GHz to get accelerating gradients up to 75 MeV/m
  - Accelerating cavities at JLab (and ILC) are superconducting f ~ 1 GHz
- "Auto-phasing" effect produces bunch structure
- RF power is generated by series of high-power klystrons with output of 60-70 MW

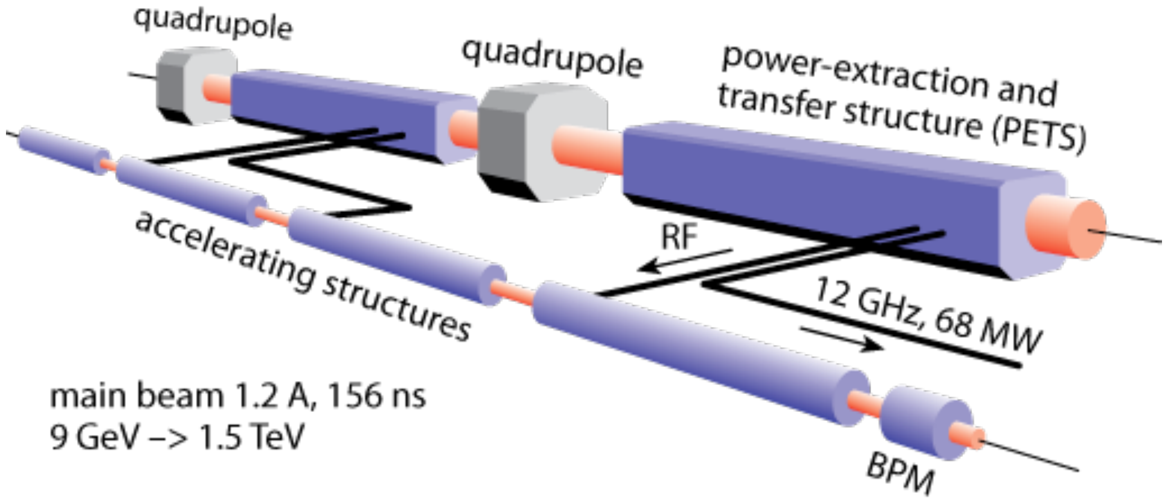






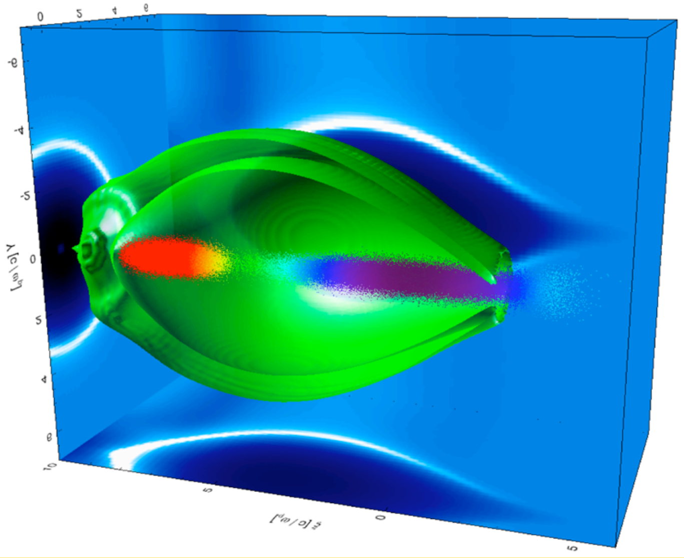
Future Accelerator Technology

- Beam-driven RF
  - CLIC

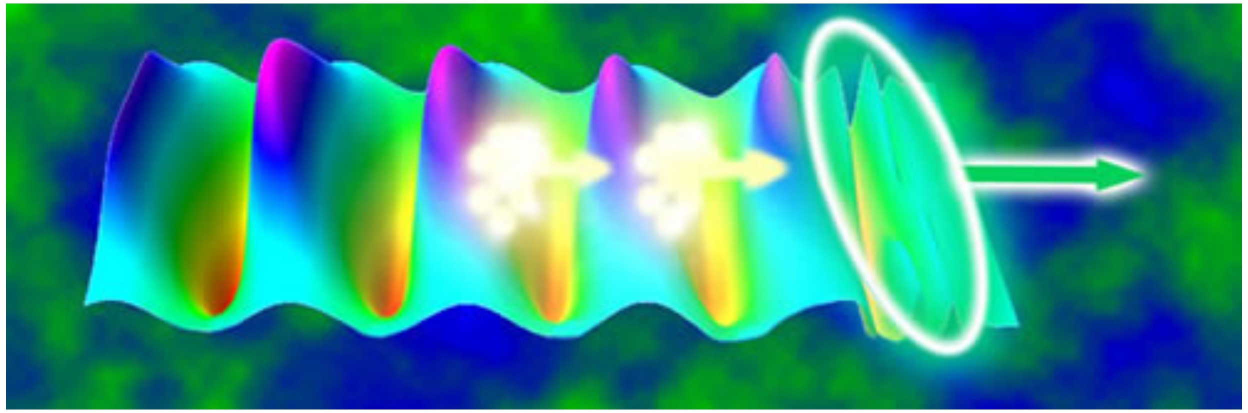


- Plasma Wakefield

Beam-driven



Laser-driven



Synchrotron Radiation

- All accelerated charges radiate. For relativistic particles in a magnetic field, radiation is called synchrotron
- Radiated power

$$P = \frac{2}{3}\frac{e^2 c}{4\pi\varepsilon_0}\frac{\beta^4\gamma^4}{\rho^2}$$

- Energy loss per particle per turn

$$U_0\ [\mathrm{eV}] = 8.85\ 10^4\ \frac{E^4\ [\mathrm{GeV}]}{\rho\ [\mathrm{m}]} = 2.65\ 10^4\ E^3[\mathrm{GeV}]\ B\ [\mathrm{T}]$$

- Grows as 4th power of energy – highest energies prohibitively expensive
- Need to increase bend radius for higher energies (but reduction is only linear)
- Examples: LEP: 100 GeV beams, 27 km circumference

Accelerator Types

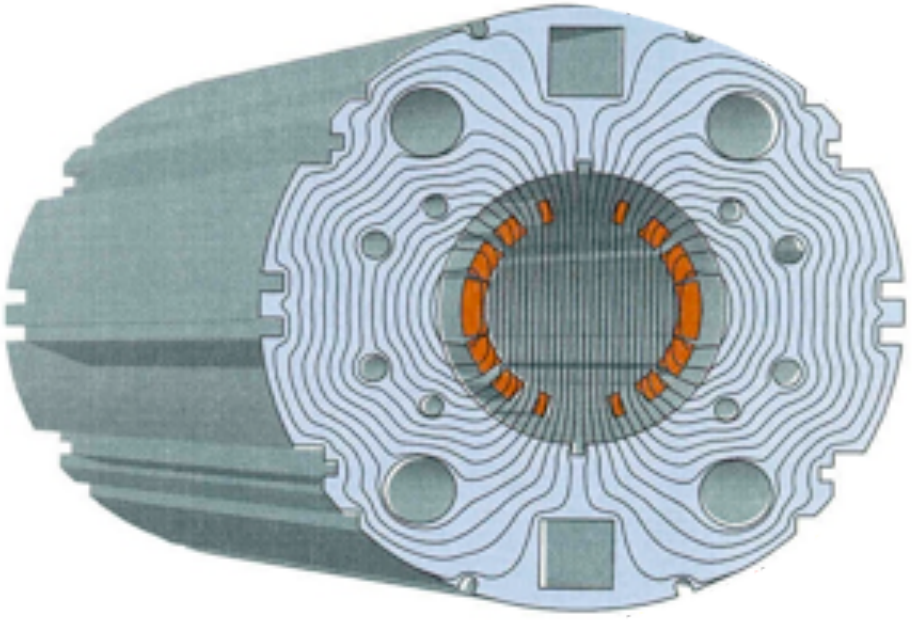
- Linear accelerators (electrons, protons)
  - Avoids synchrotron radiation losses for electrons, compact for protons
  - High gradients now available (up to 50 MeV/m)
  - But beams used only once → luminosity at a premium
  - Example: SLAC, future Linear Colliders (ILC)
- Circular accelerators: synchrotrons and storage rings
  - Highest energies possible with protons, muons
  - Synch. radiation losses for electrons
  - Multiple passes – more tolerant to errors in steering

Circular Accelerators

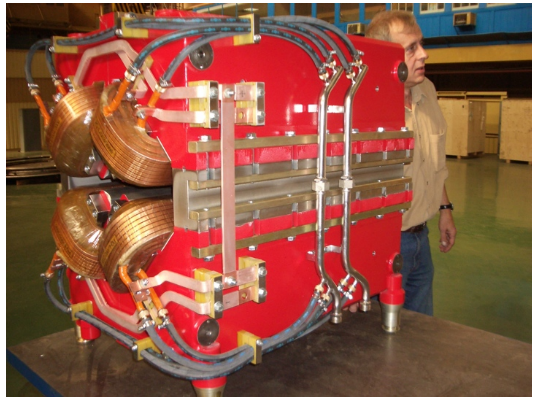
$$\boxed{p = 0.3BR} \quad (B \text{ in T}, R \text{ in m}, p \text{ in GeV})$$

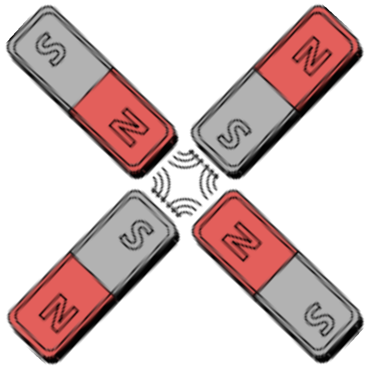
- Cyclotrons: constant *B*, variable *R*; accelerating RF electric field
  - Lawrence, 1932
- Betatrons: a little variation
  - *E* field generated by a variable *B* field (a la transformer)
- Synchrotrons: constant *R*, variable *B*, accelerating *EM* field
  - Most high-energy machines are synchrotrons

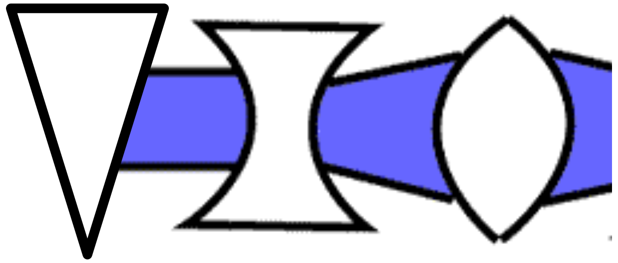
Beam Optics



- Beamlines made of a series of discrete magnets (lattice)
- Two main types of magnets
  - Dipoles: bending.
  - Quadrupoles: focusing
- Strong focusing
  - Net focusing using 1 "cell"
  - Many benefits:
    - ☞ stability
    - ☞ small beams (= compact beam pipe)
    - ☞ small beamspots (= more luminosity)







Accelerators as Secondary Particle Sources

- Fixed target facilities can produce secondary particles
  - Most common: positrons, photons, pions, kaons (including neutral K_L), muons, neutrinos
- Secondaries can be captured and accelerated
  - Anti-protons and positrons
  - Muons
  - Other species, including radioactive isotopes
- Particle decays in accelerators
  - High-brightness photon sources
  - Neutrino factories

Particle capture and cooling

- Solenoid
- Liquid-metal lens
- Particle cooling
  - ‘Phase-space’ cooling
  - Synchrotron cooling (damping rings)
  - Matter-based cooling
  - Electron cooling
  - Dynamic cooling

Other Issues

- Vacuum
  - colliders are also ‘fixed target’!
- Beam stability (higher-order correctors)
- Final Focus
  - nano-beams for SuperB, XLC
- Spin rotation (for polarized beams)
- Asymmetric (or PP) colliders
  - Finite crossing angle, bunch rotation, …
- Beam energy measurement

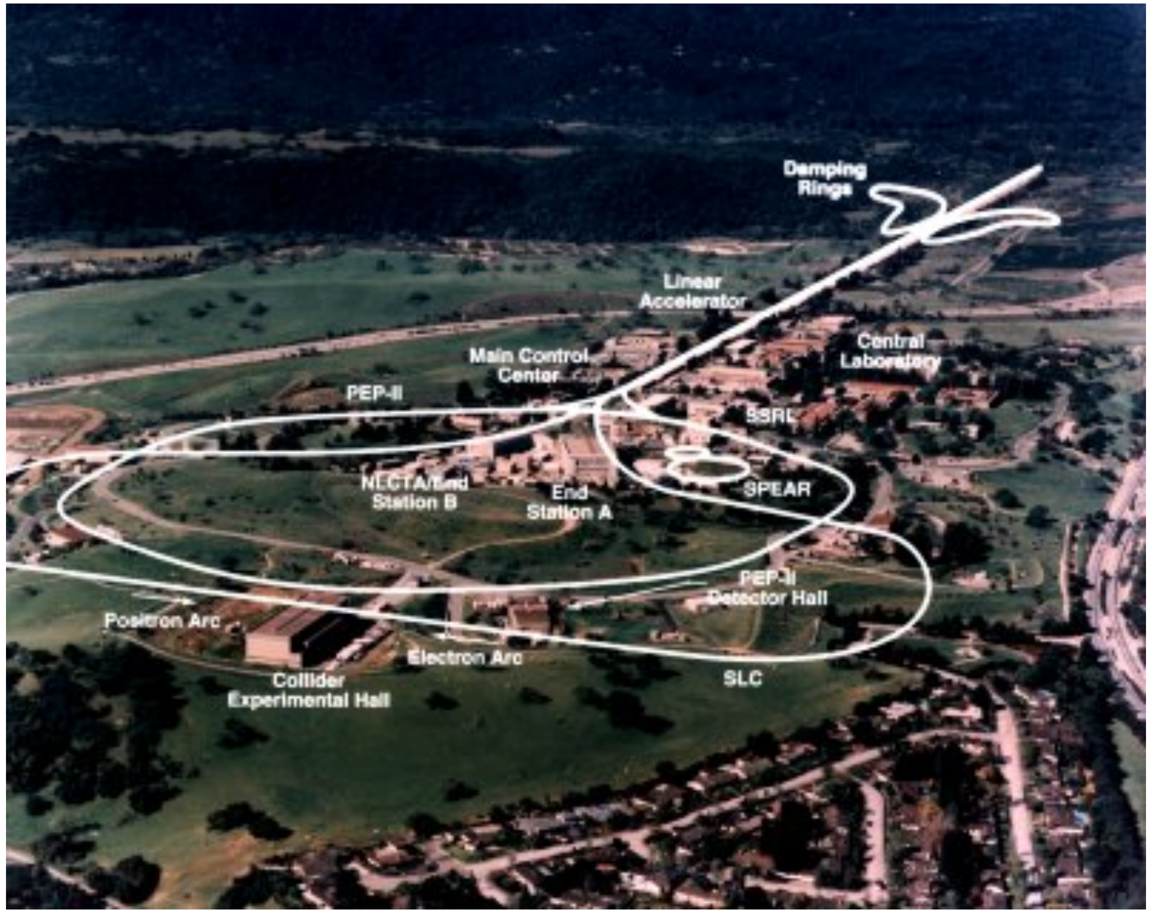
Accelerator Parameters (PDG)

https://pdg.lbl.gov/2024/reviews/rpp2024-rev-hep-collider-params.pdf

Table 32.3: Updated in March 2022 with numbers received from representatives of the colliders (contact E. Pianori, LBNL). The table shows the parameter values achieved. Design parameters for SuperKEKEB may be found in our 2018 edition (Phys. Rev. **D98**, 030001 (2018)) Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy; H and V indicate horizontal and vertical directions; s.c. stands for superconducting.

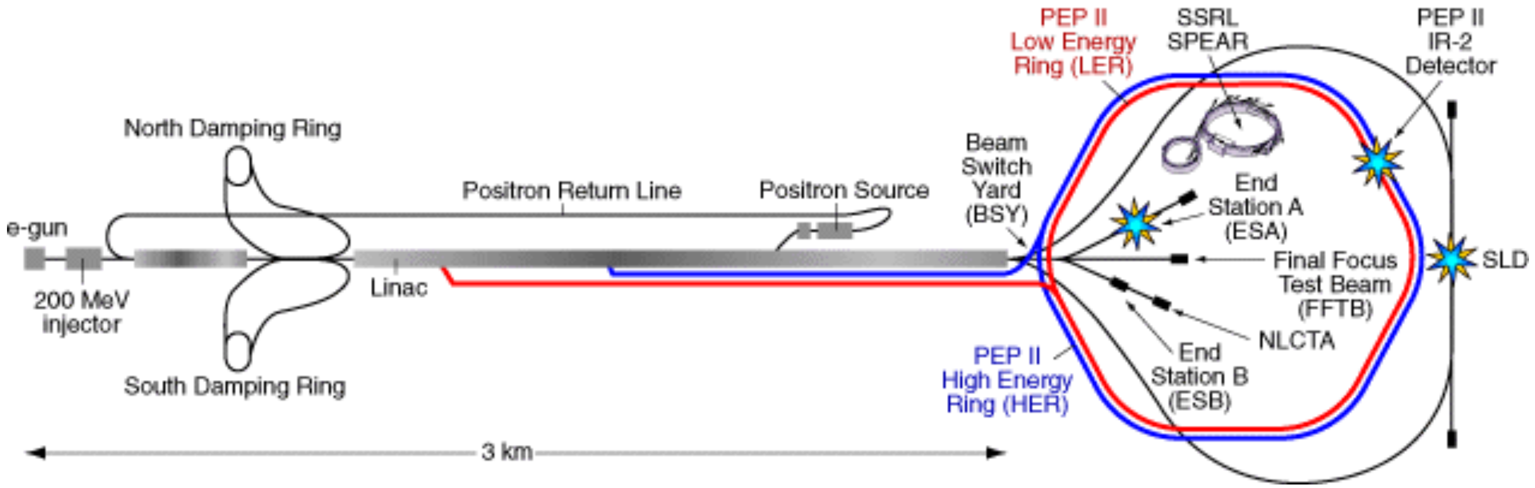
	HERA (DESY)	KEKB (KEK)	PEP-II (SLAC)	SuperKEKB (KEK)
Physics start date	1992	1999	1999	2018
Physics end date	2007	2010	2008	—
Particles collided	ep	e^+e^-	e^+e^-	e^+e^-
Maximum beam energy (TeV)	e: 0.030 p: 0.92	e^-: 8.33 (8.0 nominal) e^+: 3.64 (3.5 nominal)	e^-: 7–12 (9.0 nominal) e^+: 2.5–4 (3.1 nominal)	e^-: 7 e^+: 4
Delivered integrated luminosity per exp. (fb^{-1})	0.8	1040	557	491
Luminosity (10^{30} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	75	21083	12069 (design: 3000)	4.71×10^4
Time between collisions (ns)	96	5.9 or 7.86	4.2	4.2
Full crossing angle (μ rad)	0	$\pm$11000*	0	$\pm$41500
Energy spread (units 10^{-3})	e: 0.91 p: 0.2	e^-/e^+: 0.67/0.73	e^-/e^+: 0.61/0.77	e^-/e^+: 0.64/0.81
Bunch length (cm)	e: 0.83 p: 8.5	0.65	e^-/e^+: 1.1/1.0	e^-/e^+: 0.6/0.6
Beam radius (μm)	e: 110 (H), 30 (V) p: 111 (H), 30 (V)	H: 124 (e^-), 117 (e^+) V: 1.9	157 4.7	e^-: 16.6 (H), 0.22 (V) e^+: 17.9 (H), 0.22 (V)
Free space at interaction point (m)	$\pm$2	+0.75/−0.58 (+300/−500) mrad cone	$\pm$0.2, $\pm$300 mrad cone	e^- : +1.20/ − 1.28 e^+ : +0.78/ − 0.73 (+300/−500) mrad cone
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	10	continuous	continuous	continuous
Turn-around time (min)	e: 75, p: 135	continuous	continuous	continuous
Injection energy (GeV)	e: 12 p: 40	e^-/e^+ : 8.0/3.5 (nominal)	e^-/e^+ : 9.0/3.1 (nominal)	e^-/e^+ : 7/4

SLAC Accelerator Complex



Past glory…

- 50 GeV electron and positron beams
- Collider (SLD) and fixed target facilities
- Injector for PEP-II storage ring
- SPEAR: separate ring

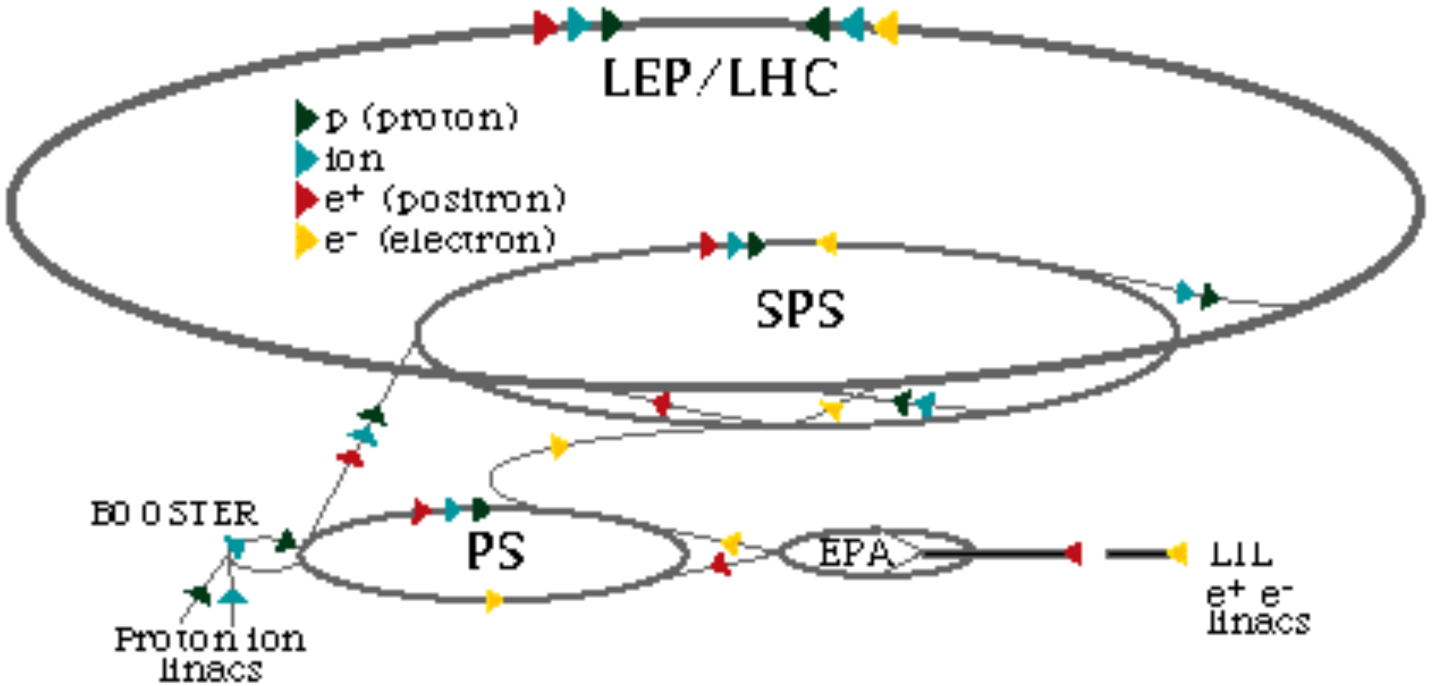


Fermilab Complex

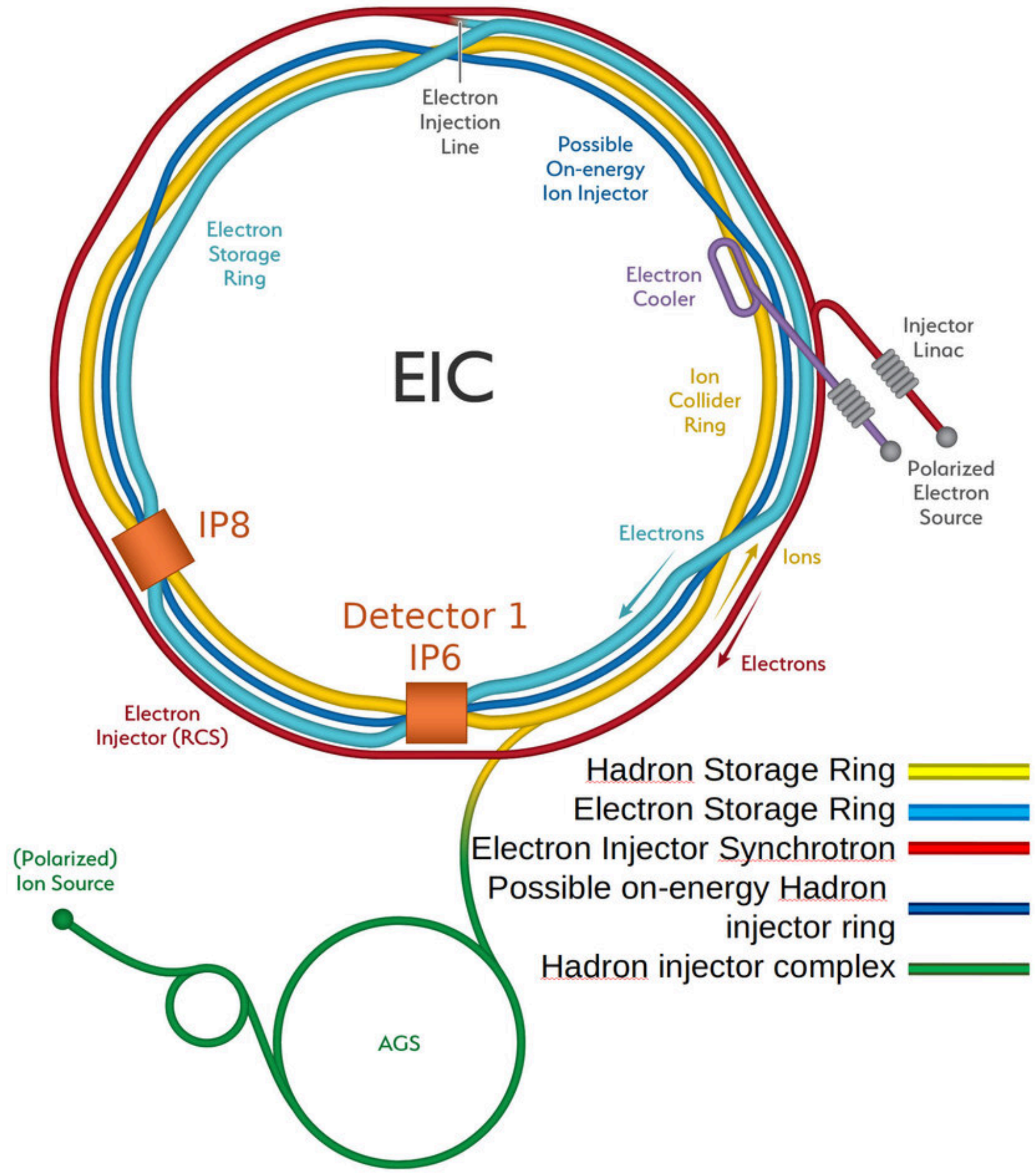
- Main Tevatron ring: 1 TeV protons and antiprotons (RIP)
- Main injector: 120 GeV booster
  - Now used for neutrino beams
- 8 GeV complex
  - Injector for the MI/Tevatron: now used for muon/neutrino beams
- Superconducting magnet technology

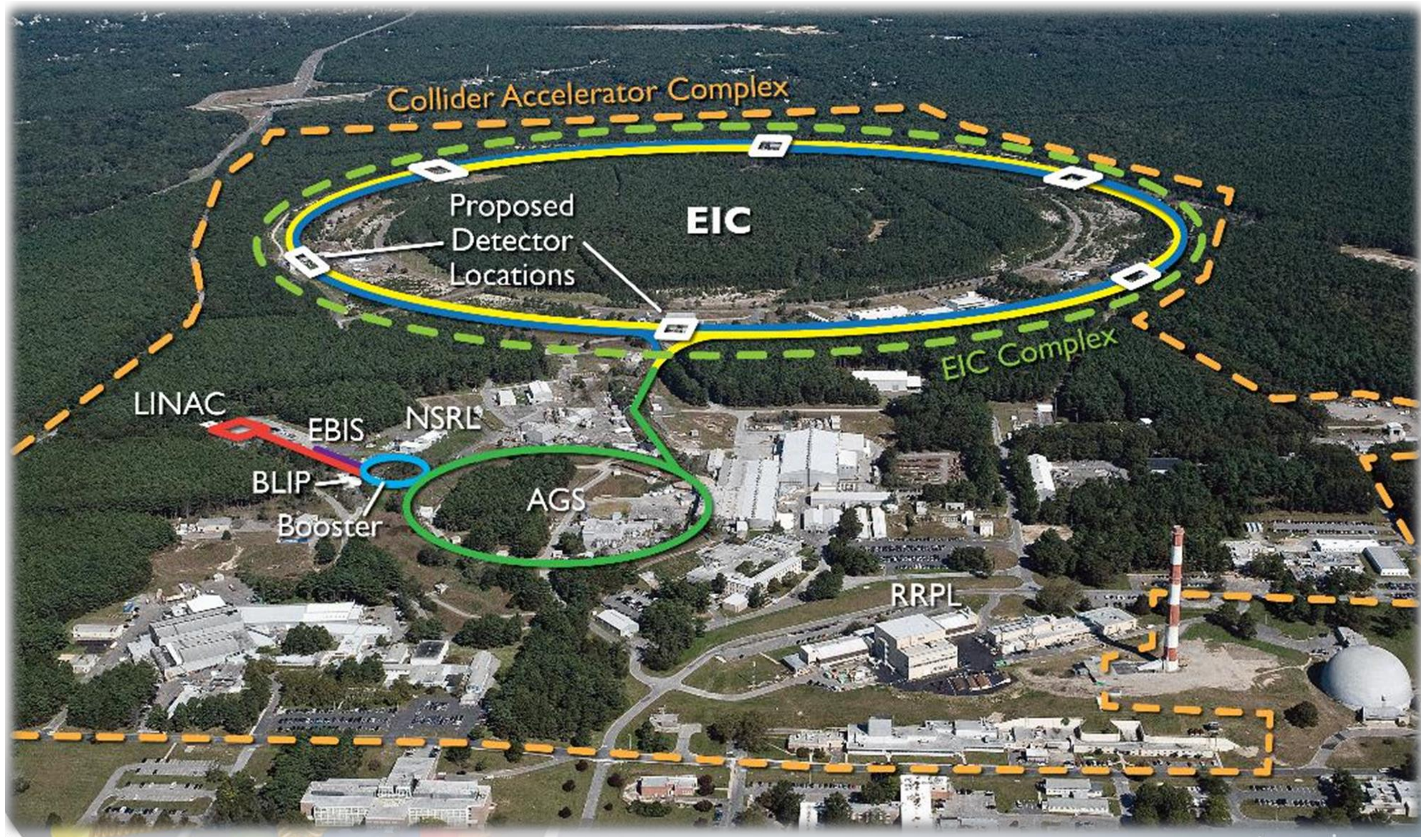
CERN

- LEP: 100 GeV electrons and positrons
- LHC: 7 TeV protons
- Same tunnel, new magnets, RF



Electron Ion Collider





Future Accelerators

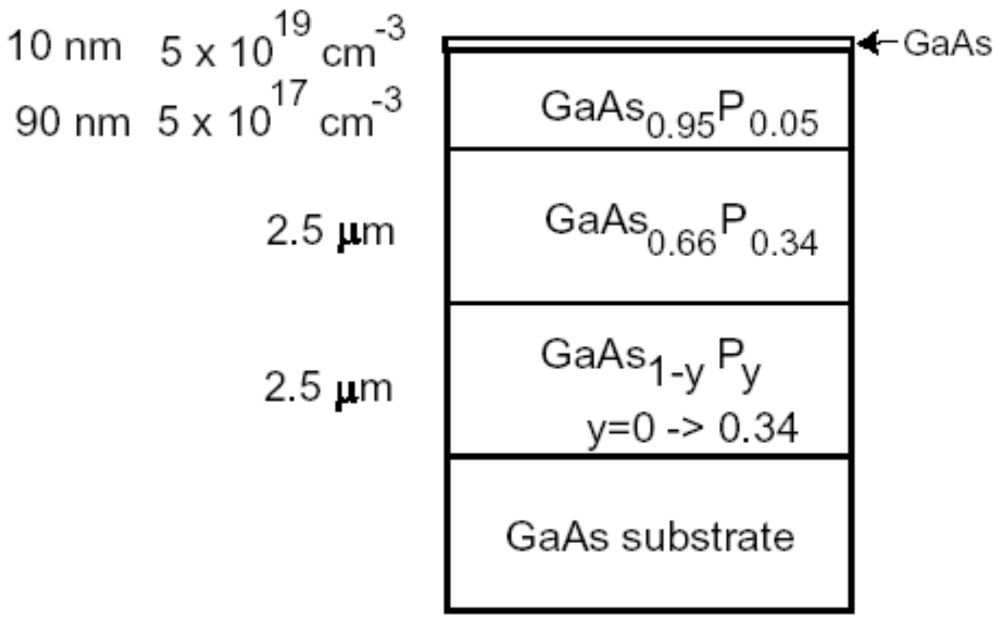
- Will certainly want to extend the energy frontier beyond the current generation of facilities
  - Probe deeper into the mysteries of the microworld
- Most straightforward: proton machines
  - FCC etc: E_{CM}> 50 TeV (+possible intermediate stages in e+e- mode)
- Complementarity: lepton machines
  - Electron linear colliders: ILC (R&D), E_{CM} > 500 GeV, CLIC: E_{CM}= 3 TeV, FCC-ee
  - Muon colliders: E_{CM}>3 TeV (R&D, possible future)

Supplemental material

Polarization

- Spin is the basic quantum number
- Electroweak couplings are helicity-specific
- Access to polarized beams and/or targets provides additional degree of freedom
  - Precision electroweak studies of couplings
  - Precision studies of nucleon structure
- Polarized sources:
  - Semiconductor photocathodes (electrons)
  - Sokolov-Ternov effect (electrons/positrons)
  - Secondary production (positrons, protons)
  - Electron or laser cooling (protons)
- Polarized targets
  - Optical pumping
  - Dynamic nuclear polarization

Example: Polarized Source Photocathode



Reference: T. Maruyama et al., SLAC-PUB-9133, March 2002; (submitted to Nucl. Inst. Meth. A)

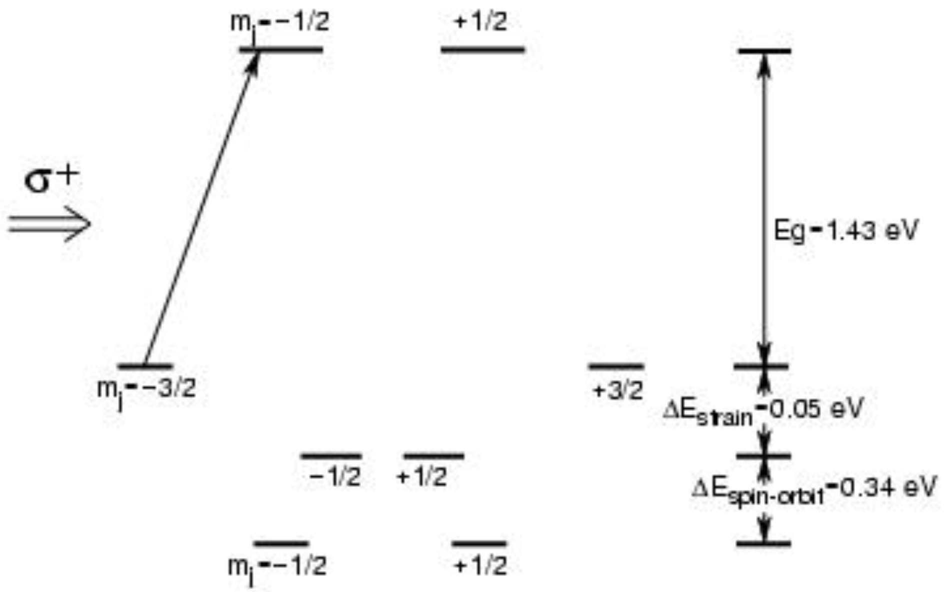
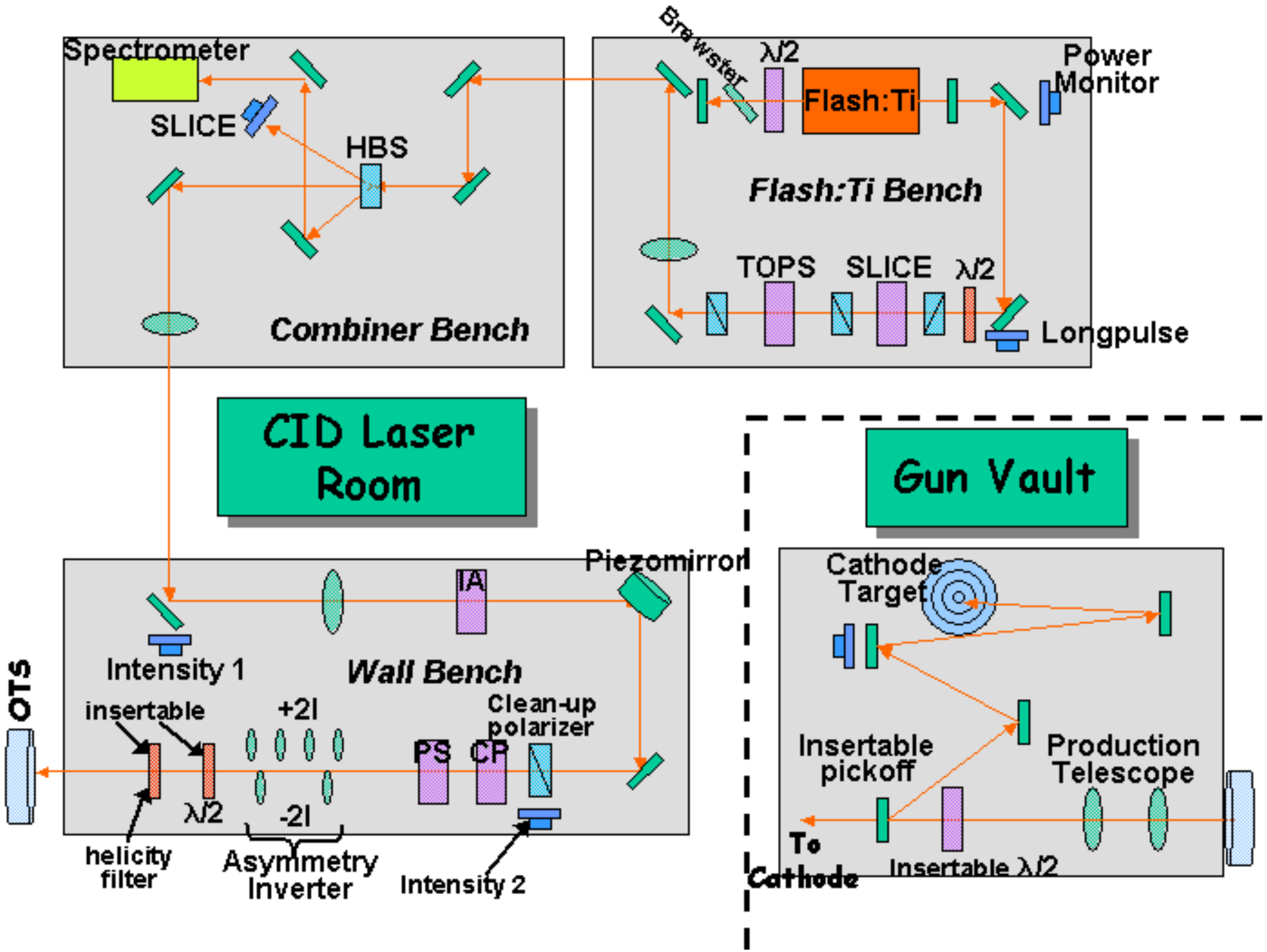


Fig. 2.2. Energy levels in strained GaAs.

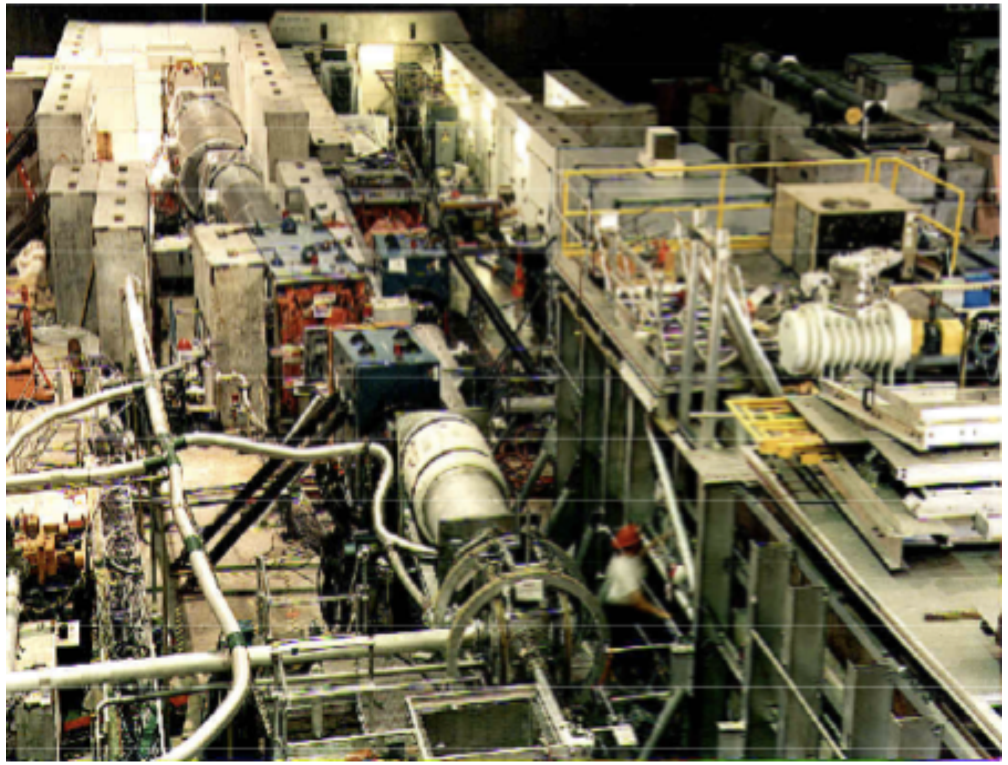
NOTES:

1. High polarization (>80%) and available charge (~10^{11} electrons/pulse)
2. Non-strained cathodes: limit 50% polarization
3. Small anisotropy in strain: ~3% analyzing power for residual linear polarization

Polarized Laser System



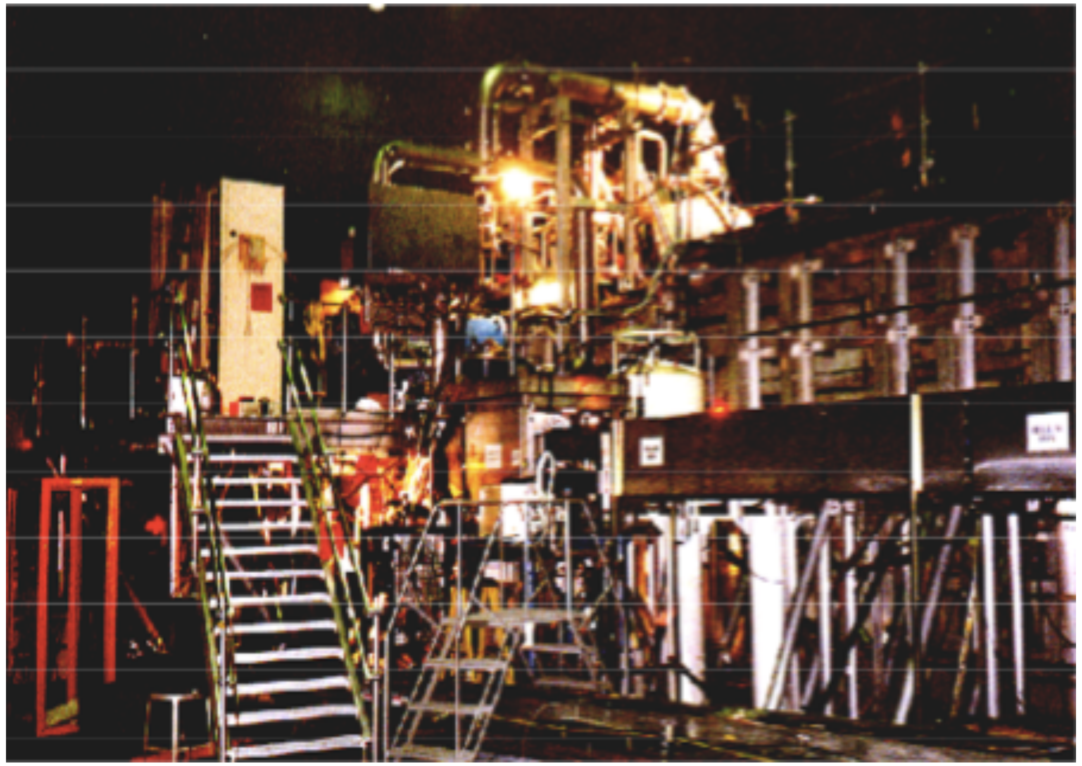
Target Technology



E154 ^{3}He Target and Spectrometers

E155: NH_3, ND_3, ^6LiD

5 Tesla Superconducting Microwave Target



CERN: Cryogenic Targets

- CERN: $5*10^7$ of polarized μ per SPS cycle (10+ sec) (80% polarization from π decay)
- Dedicated, Low luminosity
- <u>Polarized Targets</u>
- NH_3 (80%) ND_3 (50%)