PHYS 6610: Graduate Nuclear and Particle Physics I

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I. Tools

2. Particle Sources

Or: Where Your Bullets Come From

References: [HG 2, 19.5; PDG 30, 31, 38]

(a) Non-Accelerator Sources: Radioactive Sources

Radiactive Material

- α (^{4}He) source (discrete): e.g. $^{226}\mathrm{Ra}$: $E_{\mathrm{kin}} = 4.78, 4.60\mathrm{MeV}$ Rutherford's Gold Foil exp. 1909
- β ($\mathrm{e}^{\pm}$) source ($\mathrm{keV} - \mathrm{MeV}$, continuous): e.g. $^{90}\mathrm{Sr}$: $0.55\mathrm{MeV}$ PET scans, cancer treatment,...
- γ source ($0.1 - 3\ \mathrm{MeV}$, discrete): Mössbauer-spectroscopy,...
- ...

Reactor Neutrons mean neutron life-time $[878.4 \pm 0.5]\mathrm{s}$ (15 minutes)

produced by fission: $E_{\mathrm{kin}} \sim 8\mathrm{MeV}$ (typ. single-n binding energy)

scattering on low-A material (paraffin, C,...: ball on ball) moderates (decelerates) down to desired E

no elmag. interaction $\Longrightarrow$ large penetration

tune de-Broglie-wavelength $\lambda = \dfrac{1}{\mathrm{momentum}}$ to resolution

thermal neutrons $E_{\mathrm{kin}} \approx \frac{1}{40}\mathrm{eV} = 300\mathrm{K} \Longrightarrow \lambda = 2$ Ångstrom:

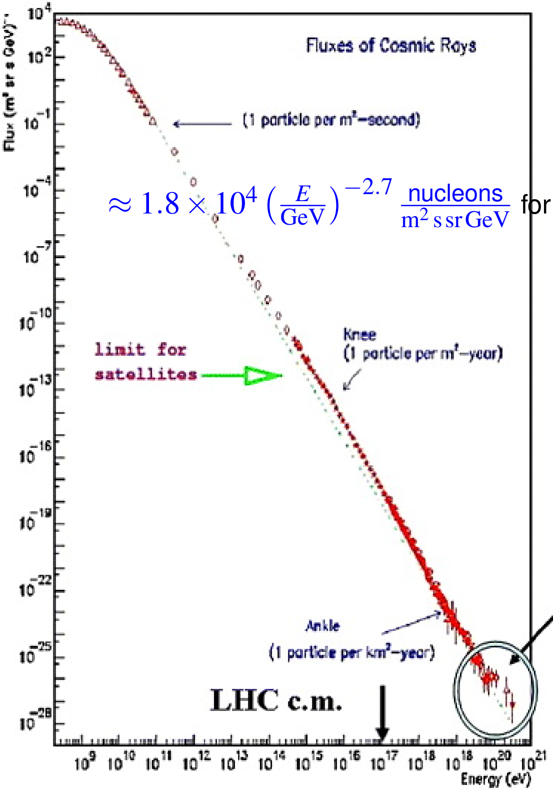
condensed matter, biology, in-time analysis,...

ultra-cold neutrons $E_{\mathrm{kin}} \approx 10^{-7}\mathrm{eV} = 10^{-4}\mathrm{K} \Longrightarrow$ speed $\approx 10\frac{\mathrm{m}}{\mathrm{s}}$:

can be trapped $\Longrightarrow$ neutron lifetime, subject to gravity, beyond-SM,...

(b) Non-Accelerator Sources: Cosmic Rays [HG 19.5, PDG 30]

Cosmic rays: primary shower



Cosmic ray spectrum year 2000

$\approx 1.8\times10^4\left(\frac{E}{\text{GeV}}\right)^{-2.7}\frac{\text{nucleons}}{\text{m}^2\,\text{s}\,\text{sr}\,\text{GeV}}$ for $\text{GeV}-100\text{TeV}$ [PDG]

~ $1 / E^3$

1 particle/km²/century

produced by supernovae, black holes, cosmic events,...

Contains any particle with life-time $> 10^6$ years, energies well beyond LHC

fight tiny rates

$\Longrightarrow$ **A**lpha **M**agnetic **S**pectrometer on ISS since 2011: search for exotics, dark matter,...

Primary shower: nuclear abundances ⟹ not from solar system

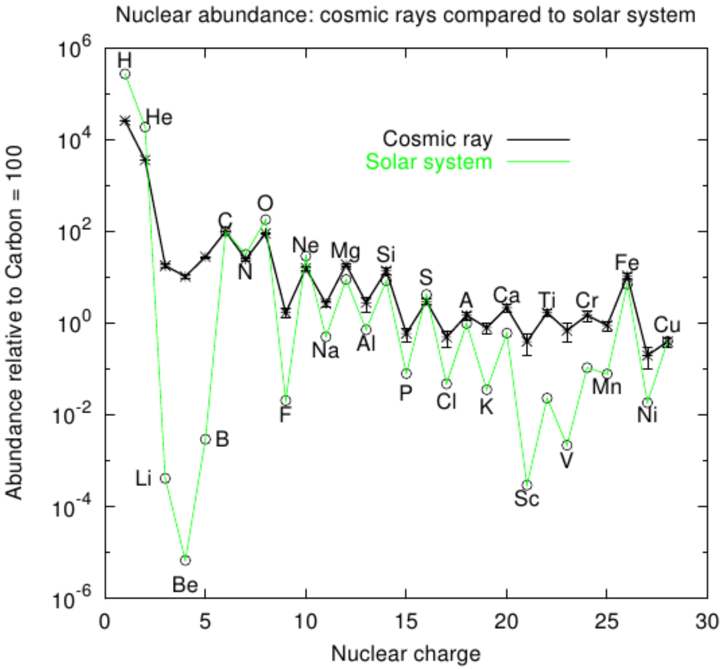
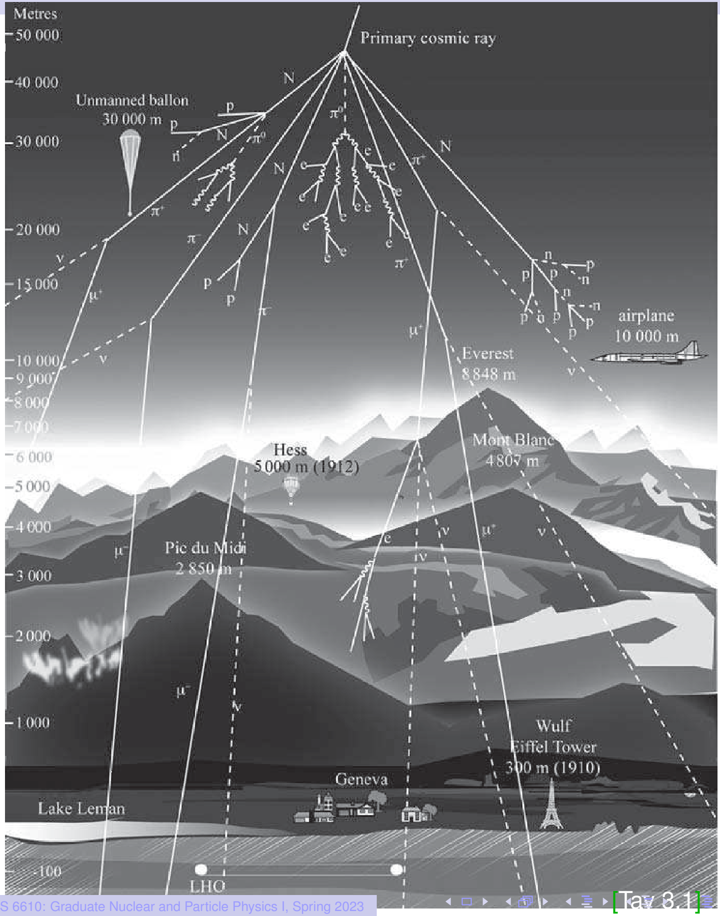


Figure 19.10: Composition of the nuclear component of the primary cosmic rays. Shown for comparison are the solar abundances. [From T.K. Gaisser and T. Stanev, *Nucl. Phys.* **A777**, 98 (2006).]

[HG]

Cosmic rays: secondary shower



[Tav 8.1]

used to discover positron (1932),

muon (1939), pion (1947),. . .

hadron core

most produced: $e^{\pm}$ by pair-production

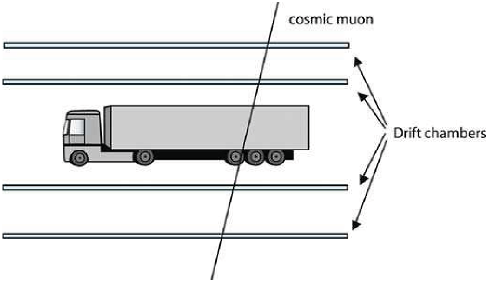
most at sea level: $\mu^{\pm}$ by time-dilatation

all other trapped above

typ. energy $2\mathrm{GeV}$

typ. rate $\dfrac{1\text{ event}}{\mathrm{cm}^2\text{ minute}}$

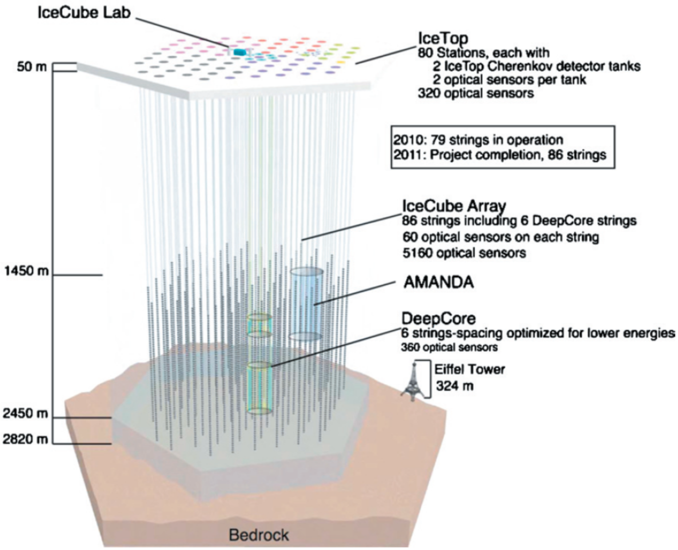
Application cargo scanning [Tav 4.22]



wait few minutes for picture

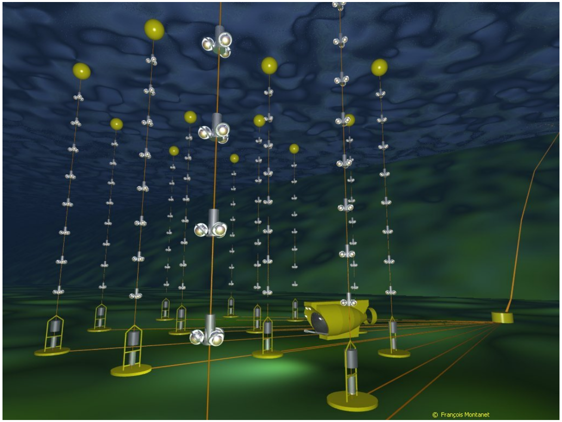
Cosmic rays: examples of secondary shower usage today

Study neutrinos (via muons), High-Energy Astrophysics,. . . $\Longrightarrow$ isolated, shielded

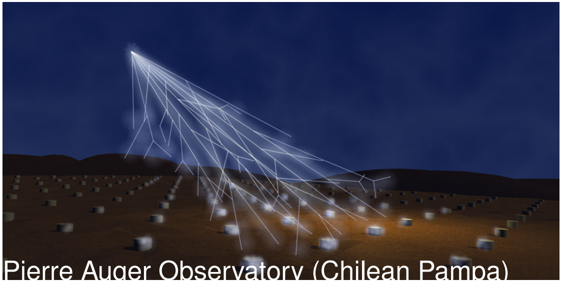


IceCube Neutrino Observatory

(ice at South Pole)



ANTARES (2.5 km under Mediterranean, France)



Pierre Auger Observatory (Chilean Pampa)

(c) Accelerator Principle

⊕: controlled environment, beam delivered on-target, any energy up to $13\,\mathrm{TeV}$ (LHC)

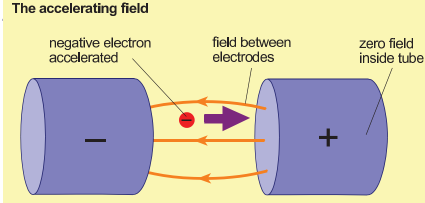
$\Longrightarrow$ match to desired resolution $\lambda = \frac{1}{p}$ (Heisenberg)

⊖: only charged particles, energies beyond reach, financial resources limited

Ingredients: accelerator physicists, source (cathode, vaporiser,. . .), vacuum pipes

accelerating & beam-focusing units use **relativistic Lorentz-force** law

$$\boxed{\frac{\mathrm{d}}{\mathrm{d}t}[\vec{p}\,] \equiv m\frac{\mathrm{d}}{\mathrm{d}t}[\gamma(\beta)\,\vec{\beta}\,] = Ze\left[\vec{E} + \vec{\beta} \times \vec{B}\right]}$$



Lorentz-factor γ depends on magnitude of velocity β!

$\Longrightarrow$ In potential difference, charge gains kinetic energy $\Delta E = Q\Delta\Phi$.

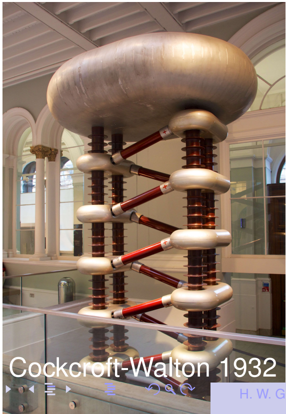
Electrostatic accelerators: cathode ray tubes

Breaking voltage of vacuum limits $\Delta\Phi \lesssim 15\,\mathrm{MV}$

cheap, enough for nuclear structure reactions

(nuclear energy levels, transmutation,. . .)

continuous beam



Cockcroft-Walton 1932

van de Graaff 1929

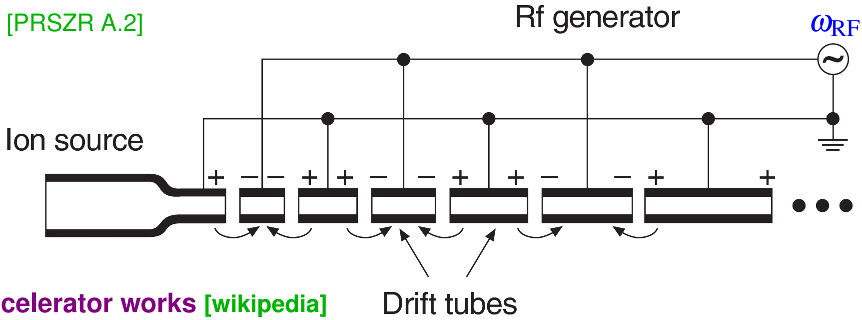
(d) Linear Accelerator: Multiple accelerations

Szilárd/
Widerøe 1928

Pulsed beam: particle bunches $\Longrightarrow$ **Reverse polarity** while charges inside "drift tubes" (field-free)

Synchronise acceleration steps by common frequency $\omega_{\text{RF}} \sim \text{MHz}$ for all tubes

[PRSZR A.2]



Movie how accelerator works **[wikipedia]**

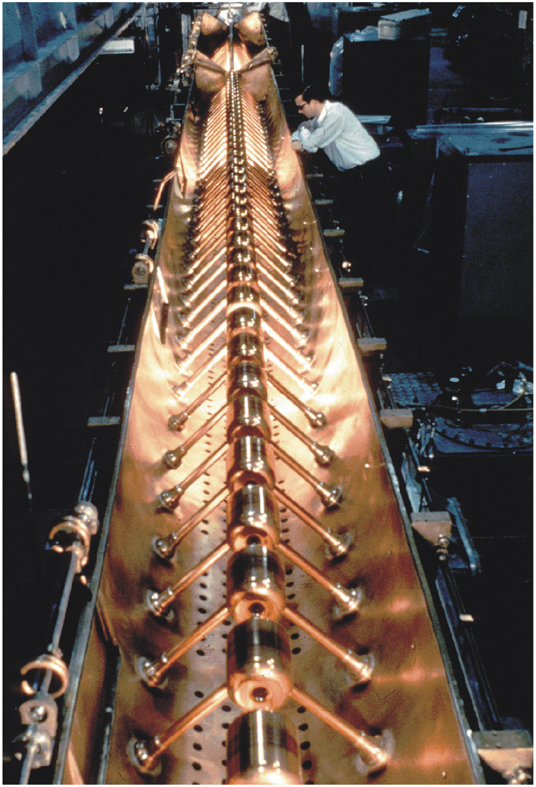
Fig. A.2. Sketch of the fundamentals of a (Wideröe type) linear accelerator. The potentials of the tubes shown are for one particular moment in time. The particles are accelerated from the source to the first drift tube. The lengths L_i of the tubes and the generator frequency ω must be adjusted to each other so that we have $L_i = v_i\,\pi/\omega$ where v_i is the particle velocity at the ith tube. This depends both upon the generator voltage and the type of particle being accelerated.

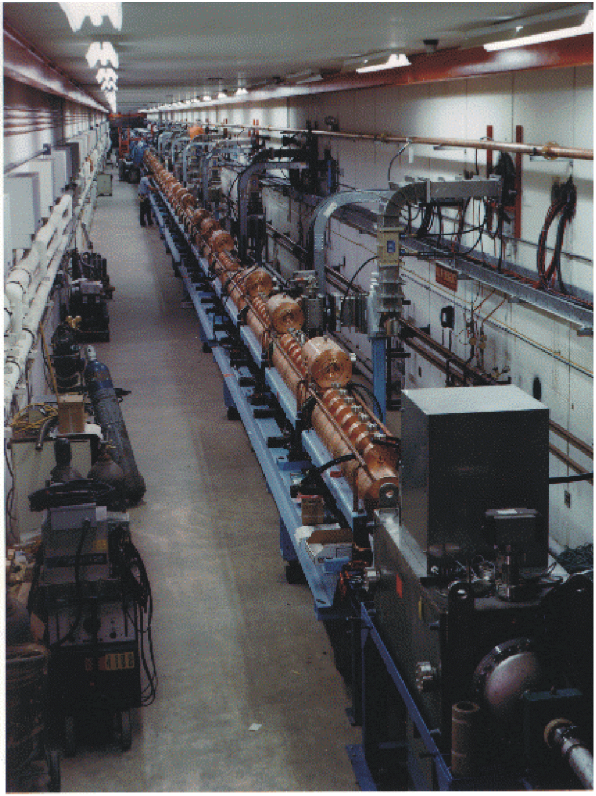
$\Longrightarrow$ **Length of i'th tube dictated by RF frequency**: $L_i = \dfrac{\pi\beta_i}{\omega_{\text{RF}}}$ grows until $v \approx c$:

$M_p \gg 15\text{MeV} \Longrightarrow$ many steps until $\beta \approx c$, drift tubes get longer

$m_e \ll 15\text{MeV} \Longrightarrow \beta \approx c$ after 1 step, drift tubes have same length

Linacs at CERN





Standford Linear Accelerator SLAC

Largest Linac: electrons to $50\ \mathrm{GeV}$ in 3km, $60\mathrm{Hz}$ pulsed beam. **Problem:** single shot, no recycling.

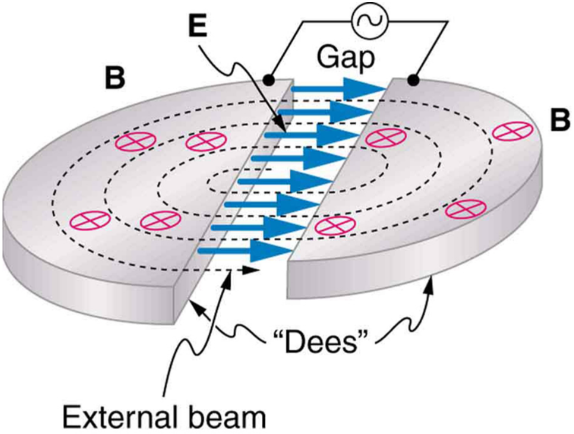
(e) Making Things Round

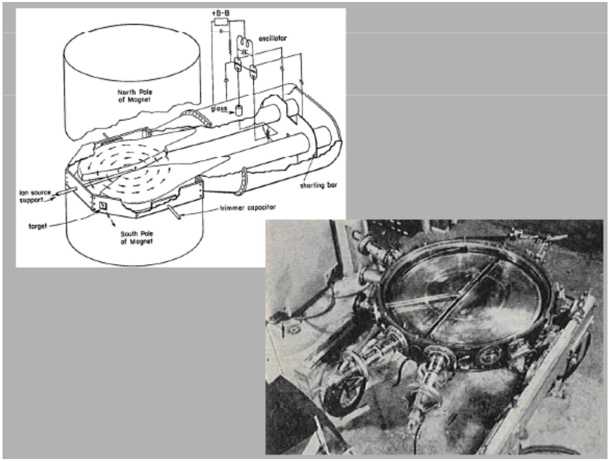
Cyclotron

[E. O. Lawrence 1930]

Circular orbit: Lorentz $Ze\,\beta\,B = \gamma m\,\omega\beta$ centrifugal (relativistic!!)

$\Longrightarrow$ $\boxed{\textbf{Cyclotron frequency of particles } \omega_C = \frac{Ze\,B}{\gamma m}}$





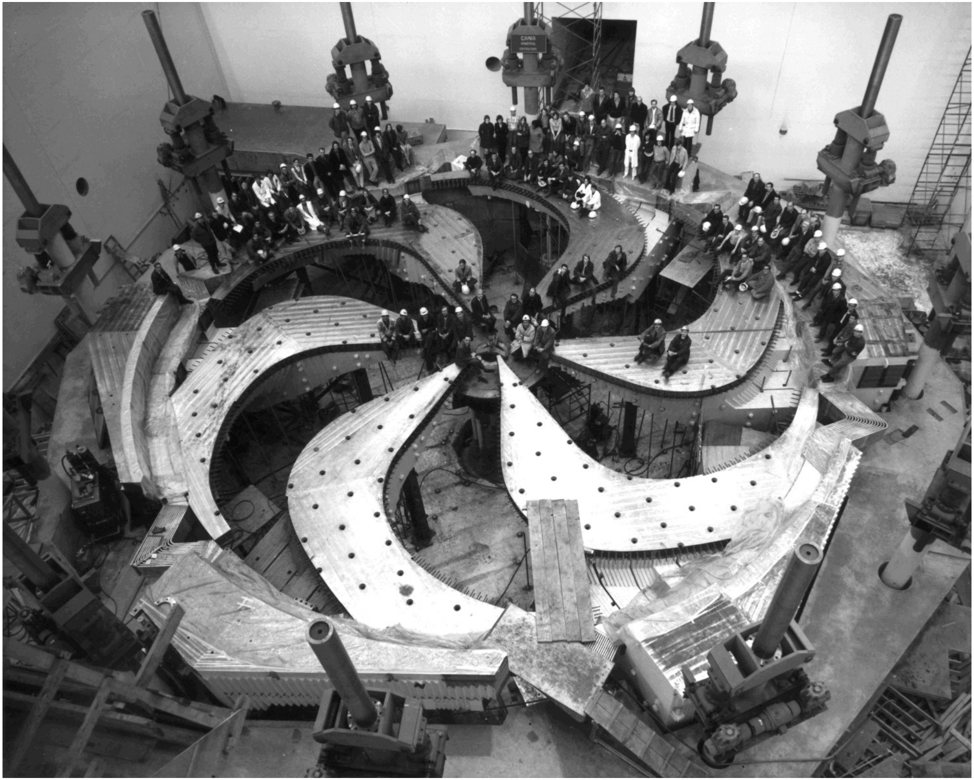
$\beta \ll 1 \Longrightarrow \gamma \approx 1$ $\Longrightarrow$ ω_C independent of particle velocity $\Longrightarrow$ can synchronise $\omega_C = \omega_{\mathrm{RF}}$ fixed!

$\Longrightarrow$ 2 accelerations per orbit inside “dees” add $\approx Z \times 15\mathrm{MeV}$, $R = \frac{p}{Ze\,B}$ increases, still **pulsed beam**

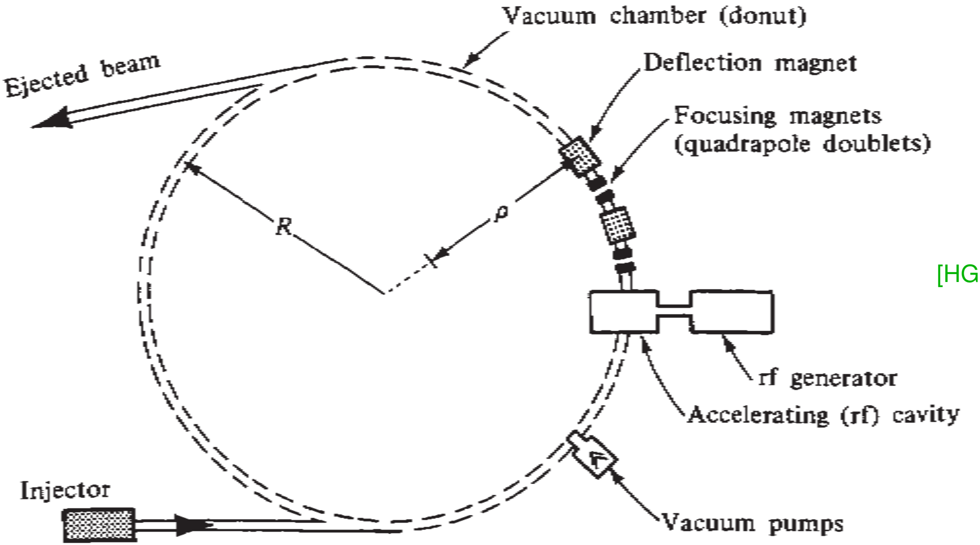
$\beta \to 1$: ω_C changes with $\gamma(\beta) > 1$ $\Longrightarrow$ no synchronous with ω_{RF} $\Longrightarrow$ bad for $e^{\pm}$ (but ok for ions).

Largest cyclotron: TRIUMF's 500 MeV for protons (Vancouver BC)

Isotope production, radioactive (secondary) beams,. . . . Click for URL



Synchrotrons: Fixed orbit $\Longrightarrow$ ramp up B in sync with ω_{RF}: Pulsed



[HG 2.10]

Several RF Cavities around ring: accelerate particle by applying high-frequency $\vec{E}$ at right timing

$$\boxed{\omega_{\text{RF}} = \text{integer} \times \omega_C = \frac{\text{integer}}{R} \text{ for } \beta \to 1.}$$

Spatial focussing into bunches by quadrupole magnets (cf. optical lenses) & *waning* part of RF-wave:

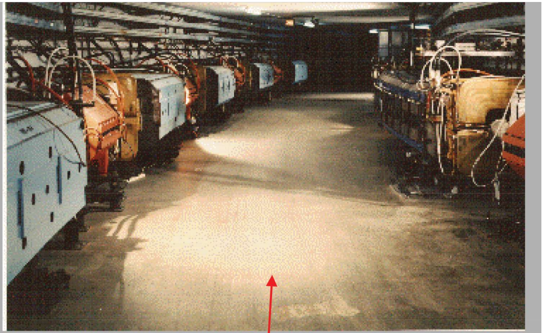
too early $\Longrightarrow$ larger $\vec{E}$ $\Longrightarrow$ more accel. $\Longrightarrow$ larger orbit at same $\beta = 1$ $\Longrightarrow$ fall back

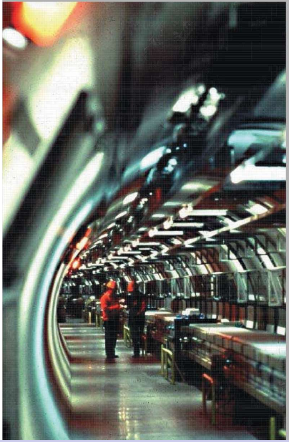
too late $\Longrightarrow$ smaller $\vec{E}$ $\Longrightarrow$ less accel. $\Longrightarrow$ smaller orbit at same $\beta = 1$ $\Longrightarrow$ catch up

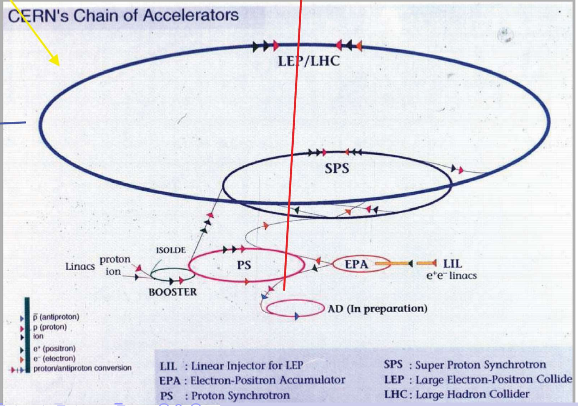
Strorage Rings typically accelerate one bunch per second

accelerate + store + collide at interaction points + recycle if unused

CERN Large Hadron Collider LHC-II: 2 rings, p/Fe on p/Fe $\leq 13\text{TeV}$, 27km circumference



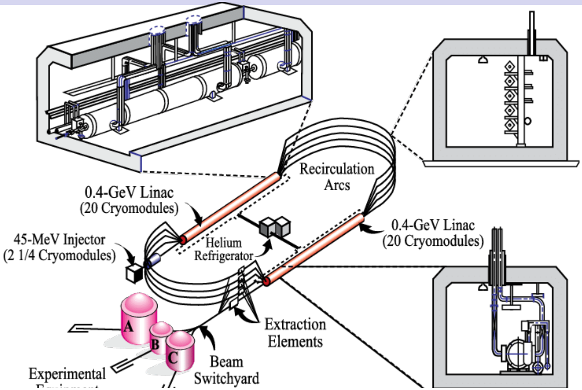




(f) Some Other “Real-Life” Accelerators

Thomas Jefferson National Accelerator Facility

Briscoe, Schmidt

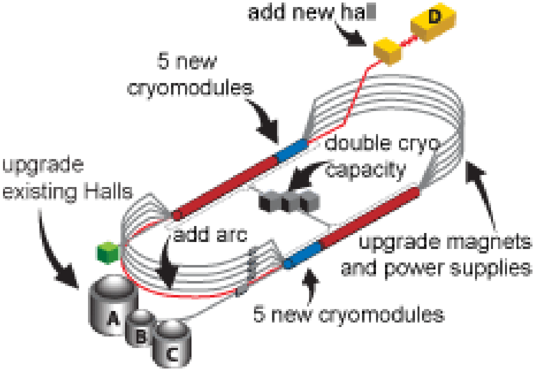


Continuous Electron Beam Accelerator Facility

Click for URL; Newport News VA;

electron “race-track”: stretched beam $\lesssim 200\mu\mathrm{A}$

$12\,\mathrm{GeV}$ upgrade for US\$310M completed in 2015



MAinz MIcrotron MAMI (Mainz, Germany)

Briscoe, Downie

Click for URL; click for article

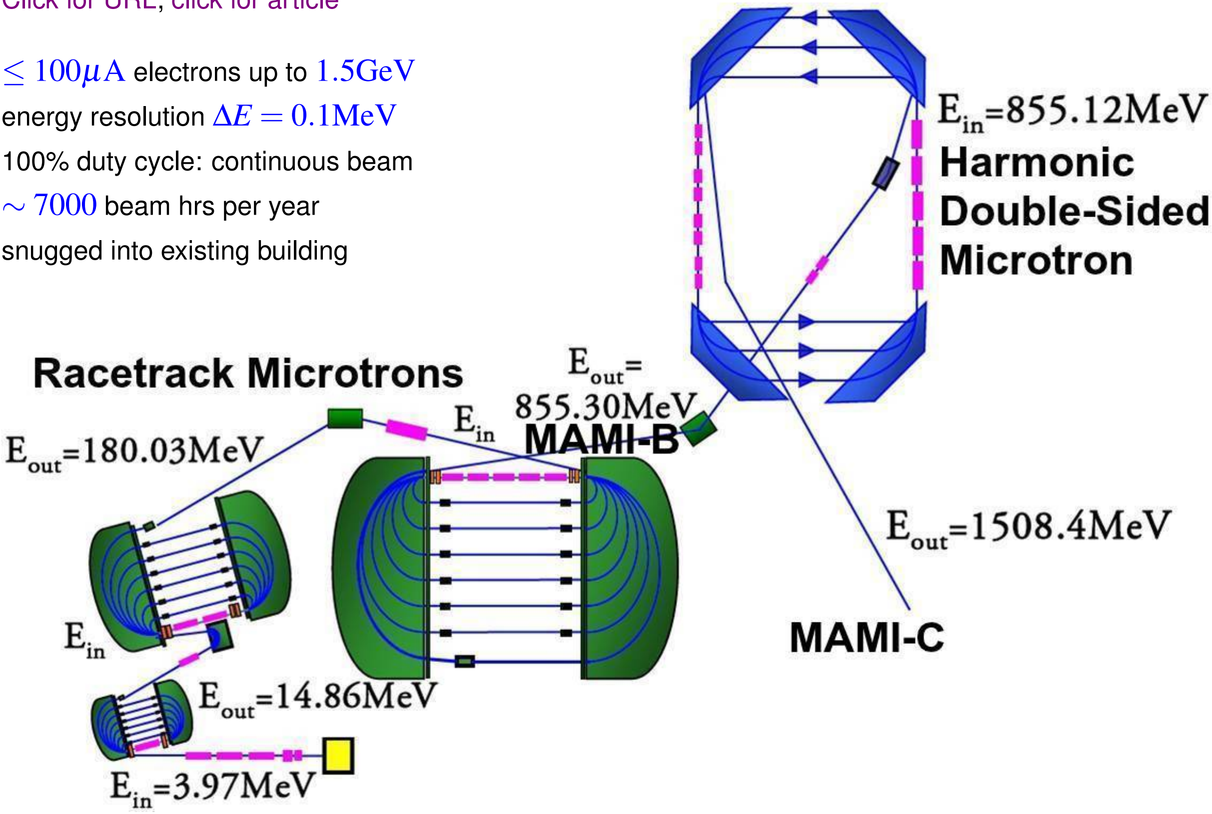
$\leq 100\mu\mathrm{A}$ electrons up to $1.5\mathrm{GeV}$

energy resolution $\Delta E = 0.1\mathrm{MeV}$

100% duty cycle: continuous beam

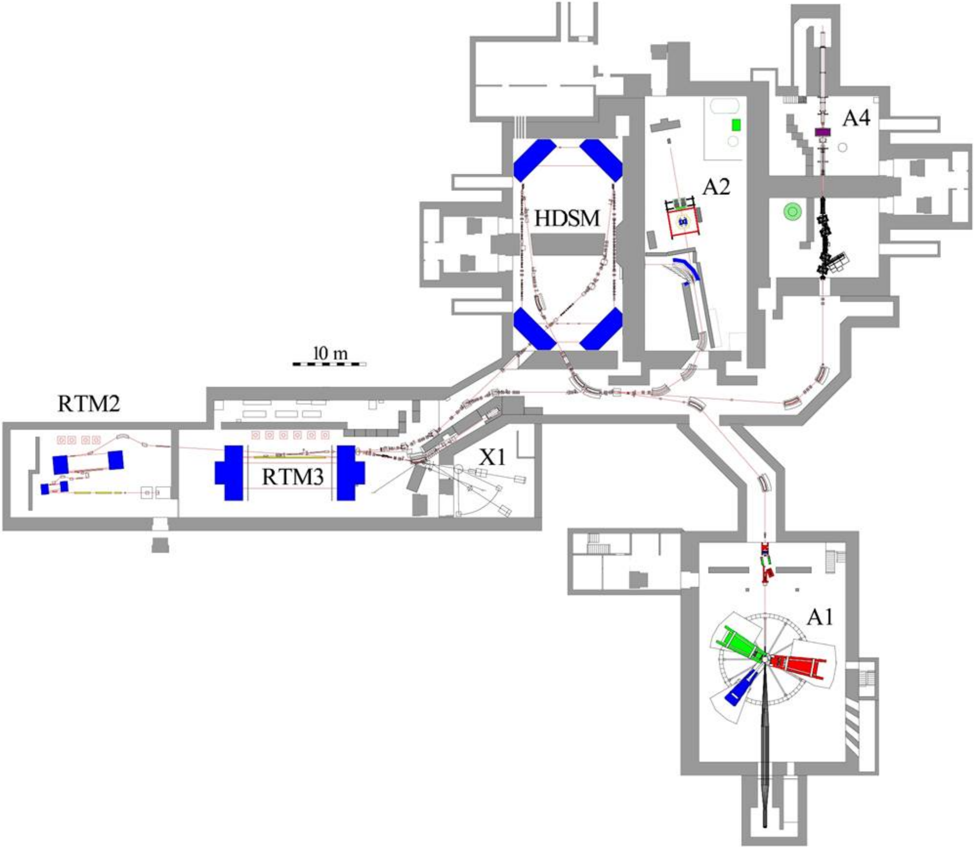
~ 7000 beam hrs per year

snugged into existing building



MAinz MIcrotron MAMI (Mainz, Germany)

Briscoe, Downie



(g) Synchrotron Radiation

[Edyn RadSys pp. 37ff, Edyn HW]

accelerated charges radiate $\Longrightarrow$ ultra-relativistic energy loss of single particle per orbit on circle:

$$\boxed{-\Delta E = \frac{4\pi Z^2 \alpha}{3} \frac{1}{R} \left(\frac{E}{m}\right)^4 \qquad \textbf{Larmor's formula (relativistic)}}$$

LEP-II (electron-positron, same tunnel as LHC): $E = 85\mathrm{GeV}$ $\Longrightarrow$ 2% energy loss

Compensate by increasing R??: 4th power vs 1st power $\Longrightarrow$ $$$!

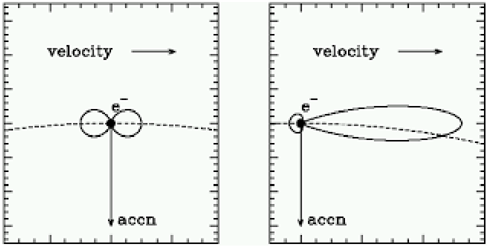
at same energy, radiation loss for proton smaller by

$$\left(\frac{m_e}{M_p}\right)^4 \approx \left(\frac{1}{1800}\right)^4 \approx 10^{-13}$$

$\Longrightarrow$ LHC-proton energy up to $14\ \mathrm{TeV}$ (limit is strength of mag. holding field for same orbit!)

HW: For $\beta \to 1$, radiation very narrowly peaked "forward", i.e. in direction of velocity $\vec{v}$.

(nonrelativistic: direction perp. to acceleration)



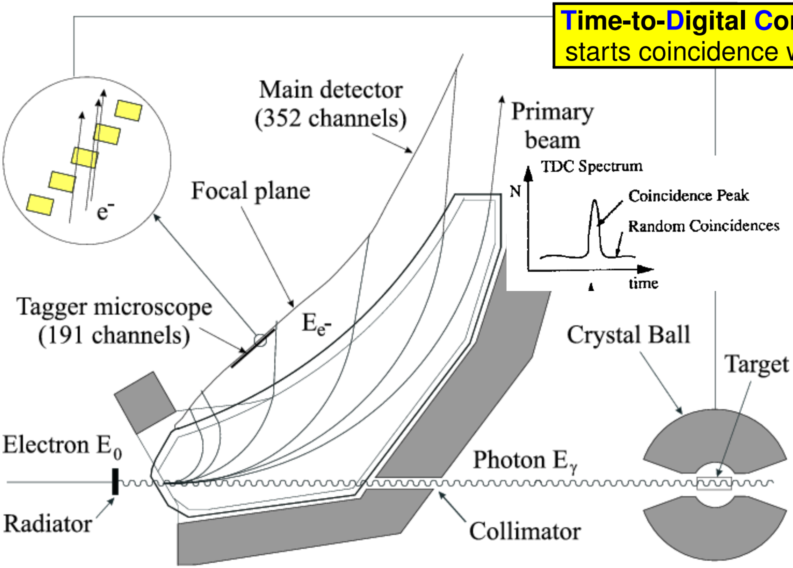
(h) Produce Photon Beams by Accelerating Charges

Tagged Photon Facility: “Glasgow Tagger” (A2@MAMI)

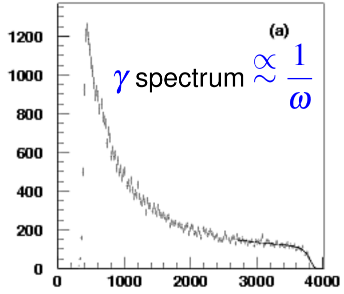
upgraded 2017
see Downie

e^- on diamond (polarised γ at MAMI) or foil (unpolarised) $\Longrightarrow$ continuous **Bremsstrahlung** spectrum

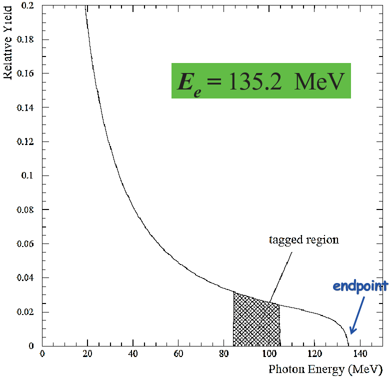
Tagging: detect momentum of deflected electron event-by-event $\Longrightarrow$ photon energy $\omega = E_0 - E_e'$



Time-to-Digital Converter
starts coincidence window



γ spectrum $\overset{\propto}{\sim} \frac{1}{\omega}$

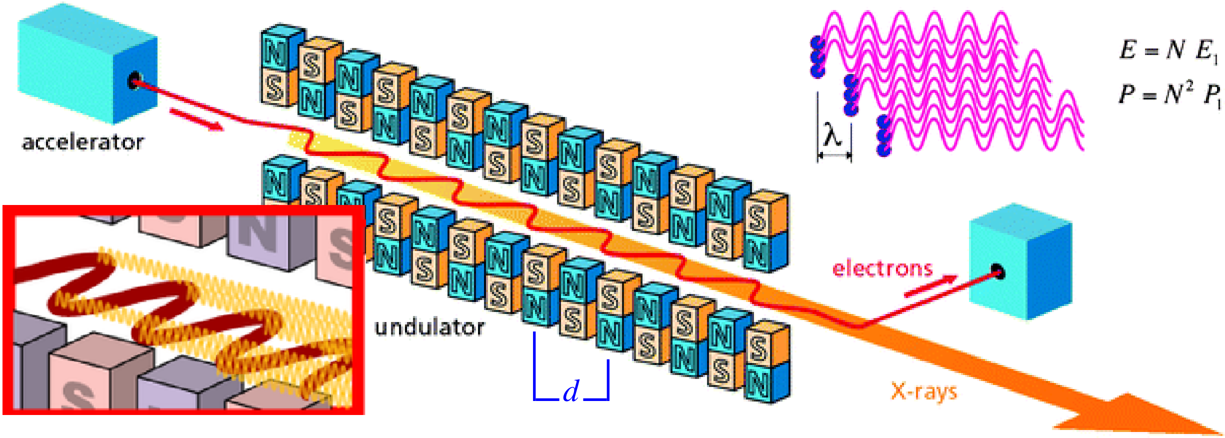


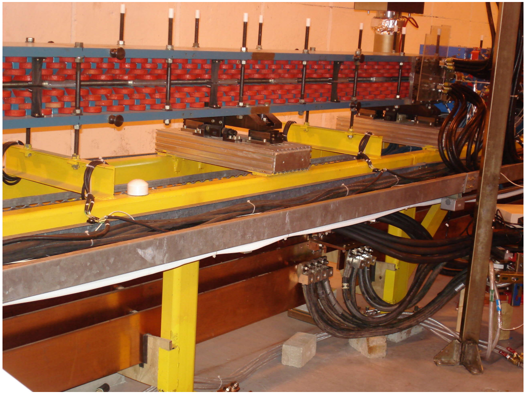
$E_e = 135.2$ MeV

Event-selector is excellent trigger to reduce background

for small-rate experiments (Compton: $\text{nanobarn} \widehat{=} \frac{\textbf{events}}{\textbf{hour}}$**).**

3rd Generation Synchrotrons and Free Electron Lasers





Undulators, period d: e^- wiggles $\Longrightarrow$ emits radiation

Lasing: e^- in bunches, tuning $\Longrightarrow$ **induced emission**

Lorentz contraction: wavelength $\frac{d}{\gamma}$ in e^- rest frame

"Radiation Always Forward" (HW): emit photon along e^-

Relativistic Doppler Effect into lab frame: $\lambda = \frac{1}{\gamma}\left(\frac{d}{\gamma}\right)$

Example: electrons at $1\mathrm{GeV} \Longrightarrow \gamma = \frac{E}{m} \approx 2000$:

$$\omega \approx \frac{2\pi\,(\gamma \sim 2000)^2}{d \sim 0.3\mathrm{m}} \approx [1\ldots10]\mathrm{eV}\text{: visible light, UV}$$

FEL $+$ Mirror $=$ Compton Backscattering Facility

Feldman, Downie (hg PAC)

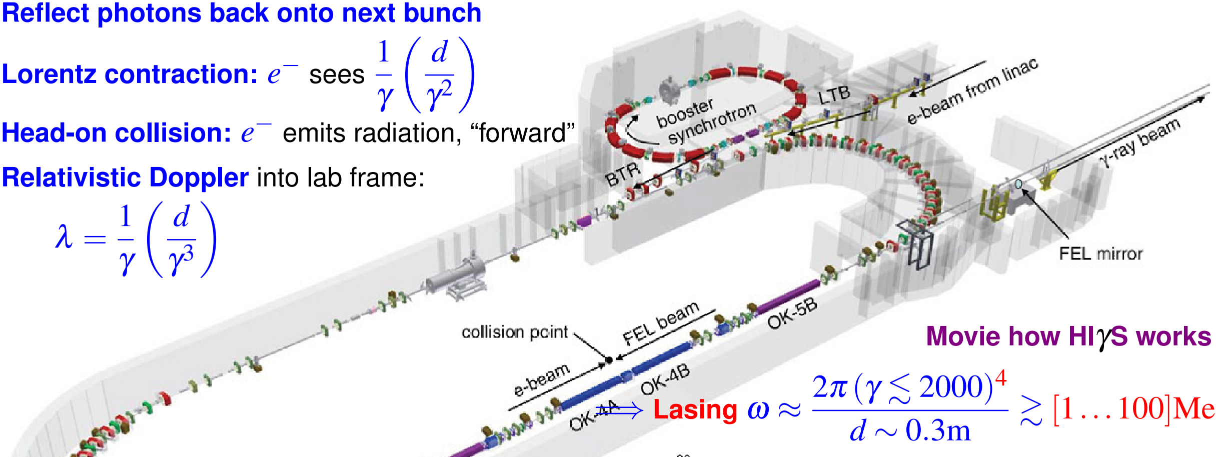
Reflect photons back onto next bunch

Lorentz contraction: e^- sees $\dfrac{1}{\gamma}\left(\dfrac{d}{\gamma^2}\right)$

Head-on collision: e^- emits radiation, “forward”

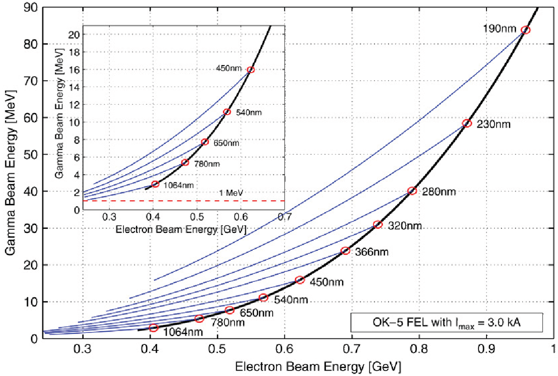
Relativistic Doppler into lab frame:

$$\lambda = \frac{1}{\gamma}\left(\frac{d}{\gamma^3}\right)$$



Movie how HIγS works

$\Longrightarrow$ **Lasing** $\omega \approx \dfrac{2\pi\,(\gamma \lesssim 2000)^4}{d \sim 0.3\text{m}} \gtrsim [1\dots 100]\text{MeV}$



e^- energy, FEL (mirror) wavelength, γ energy

High Intensity γ-Ray Facility HIγS, Duke U. (NC)

$E < 120\text{MeV}$ tunable, $\Delta E \lesssim 5\%$ quasi-monochromatic

$10^7\,\dfrac{\gamma}{s}$: **most brilliant laser**, 100% circ. or lin. polarisation

(i) Secondary Beams: neutral or short-lived particles

Some examples:

- **Neutrons:** cannot be accelerated $\Longrightarrow$ fission reactor or spallation (high-E proton on mercury), moderate down to desired E. – e.g. NIST, SNS (Oak Ridge National Lab)
- **Antiprotons:** p at e.g. $28\mathrm{GeV}$ on 60-cm Be target produces $10^{-[3...4]}$ $\bar{p}$. Store, cool, use; – e.g. CERN SPS.
- **Pions** $\pi^{\pm}$: as above, but much higher probability – mag. field separates & selects energy – e.g. $500\mathrm{MeV}$ p on C at Paul Scherer Institute PSI (Switzerland) (Briscoe, Downie)
- **Kaons** $K^{\pm}$: as above, probability $\approx 1/20$ of pion – e.g. CERN SPS.
- **Muons** $\mu^{\pm}$: ternary beam: $\pi \to \mu + \nu_{\mu}$; passage through several metres of steel. – e.g. PSI
- **High-energy neutrinos**: like muon, but shield by hundreds of metres – e.g. OPERA in the Alps.

Use time-dilatation for short-lived particles:

pion lifetime at rest: $\approx 10^{-8}\mathrm{s}$ at $E \approx p = 10\mathrm{GeV}$: $10^{-8}\mathrm{s} \times \gamma = 10^{-8}\mathrm{s} \times \dfrac{E}{m_{\pi}} = 10^{-6}\mathrm{s}$

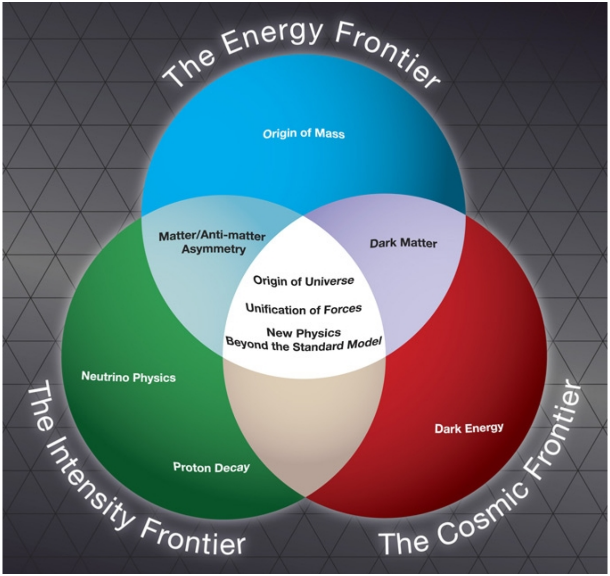
$\Longrightarrow$ pion travels distance $c \times 10^{-6}\mathrm{s} = 100$'s of metres.

secondary beams often contain several species

$\Longrightarrow$ separate by el. & mag. fields, passage through matter, good final-state ID.

(j) Future Accelerators: Examples

US Department of Energy 2009: The Three Futures of Nuclear and Particle Physics

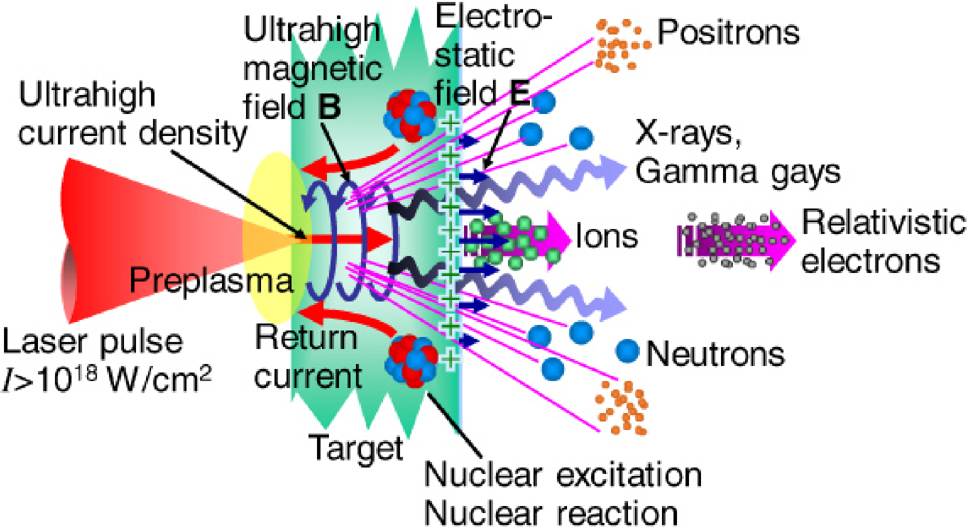


$e^{\pm}$ linear collider ILC(JP) or CLIC(EU): $1-3\mathrm{TeV}$, 2 linacs, each $15-20\mathrm{km}$ cost?? when??

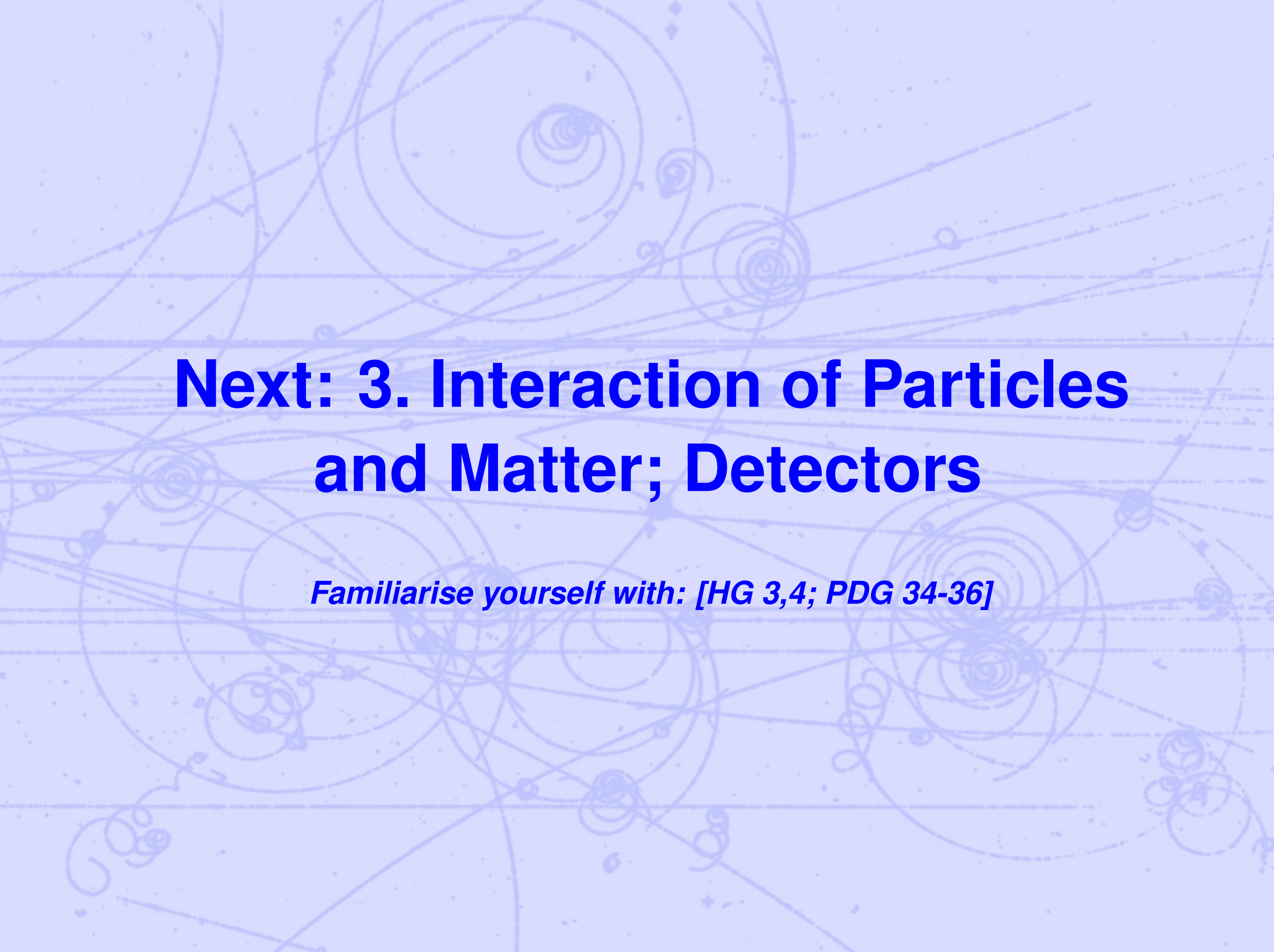
NSAC recommendation 2017: Electron Ion Collider EIC@Brookhaven 20-200GeV, $> 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Supercond. energy recovery electron linacs, e.g. MESA (Mainz): 300 MeV, 10mA, 100% polarised (construction started)

Laser-Driven “Table-Top” Accelerators (Exawatt!)



Need to re-think “single-energy” & detector concepts!



Next: 3. Interaction of Particles and Matter; Detectors

Familiarise yourself with: [HG 3,4; PDG 34-36]