

COLLIDERS

LECTURE I

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REFERENCES

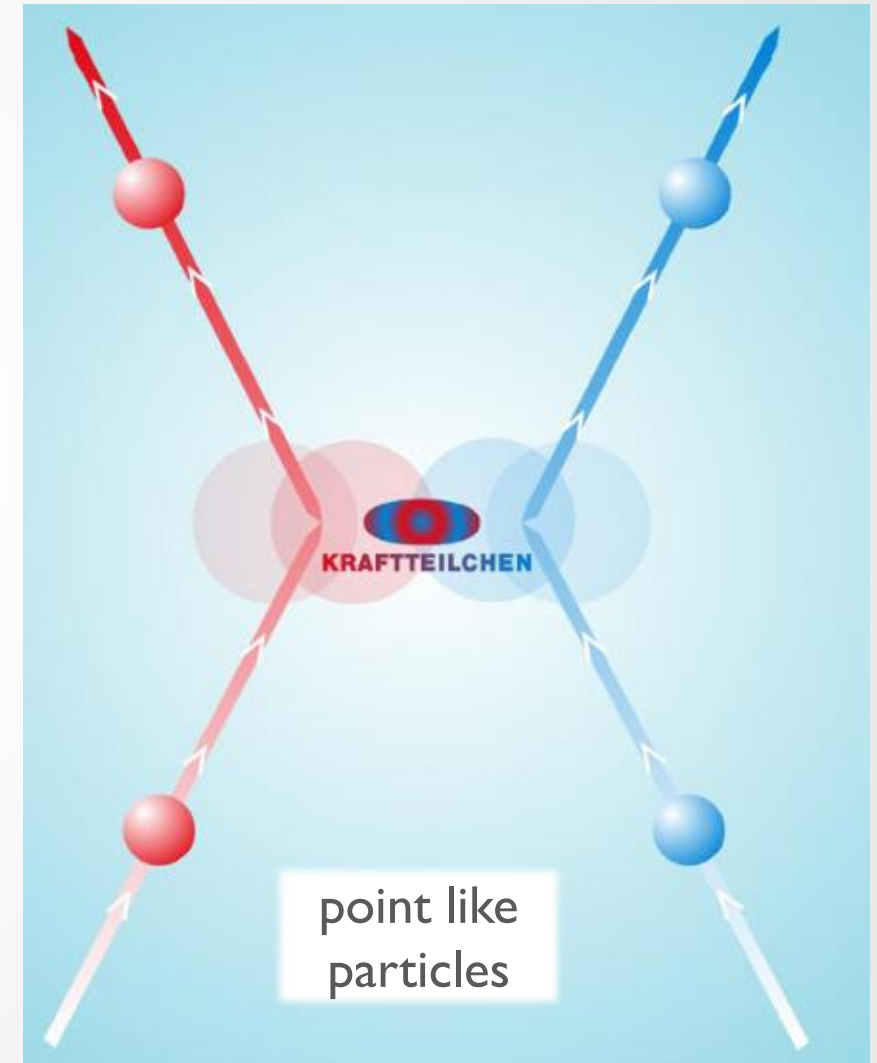
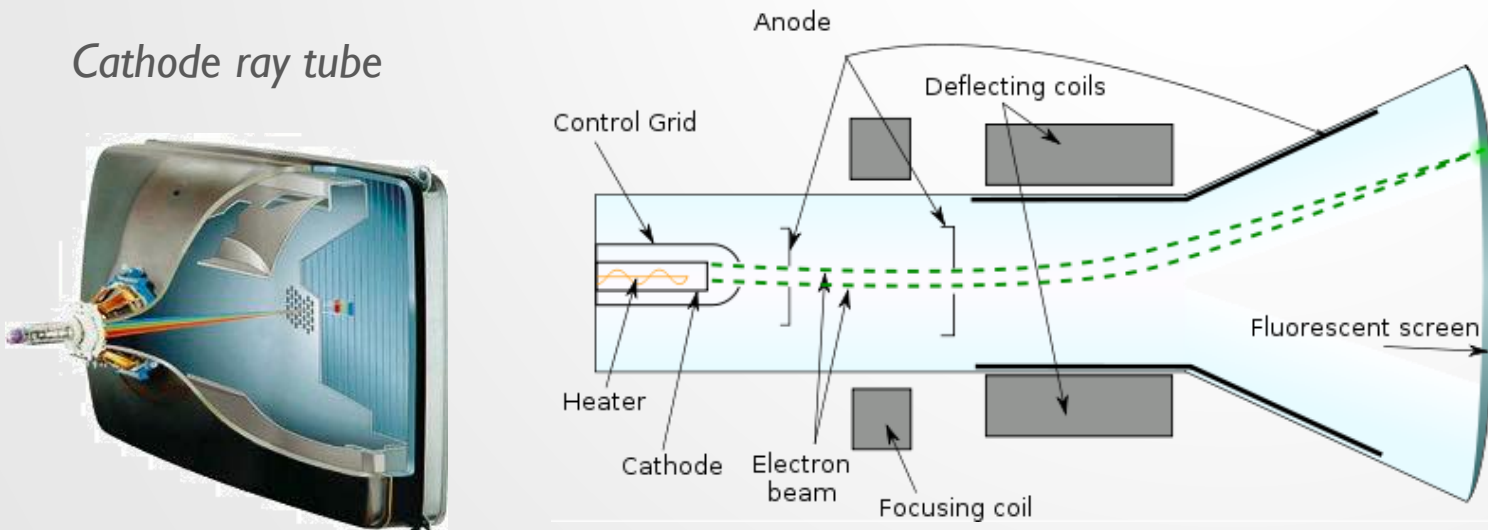
- [1] <https://www.cv.nrao.edu/course/ast534/PDFnewfiles/LarmorRad.pdf>
- [2] <https://webhome.phy.duke.edu/~rgb/Class/phy319/phy319/node146.html>
- [3] <https://apatruno.files.wordpress.com/2016/09/lecture71.pdf>
- [4] <https://cds.cern.ch/record/941318/files/p361.pdf>

I. INTRODUCTION

I.1 PARTICLE PHYSICS & ENERGY SCALES

- Investigating phenomena at ever smaller length scales requires ever higher energy, either in the lab or provided by nature.
- Because $E = \hbar k = h/\lambda$, new particles of mass m will be created if $E \geq mc^2$ unless forbidden by a conservation law.
- A 'passive' observation of structures at the shortest length-scale is thus usually not possible.
- Understanding short length scales can be done in *collision*.

Cathode ray tube



I.2 UNITS

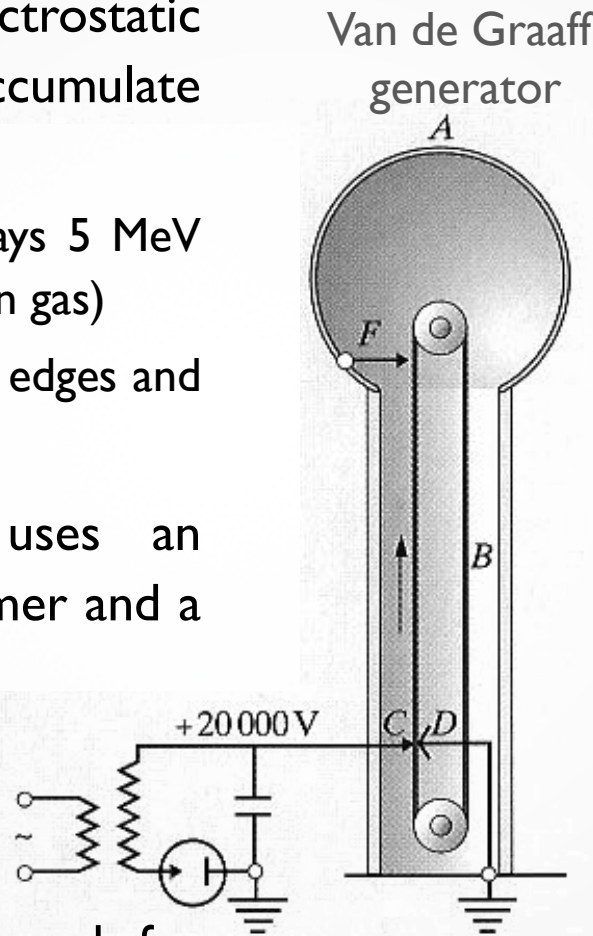
[Thomson, Modern particle physics]

- S.I. UNITS kg, m, s when relating to “everyday” objects, including EUR/USD/CHF.
- not natural in particle physics
 - instead use **Natural Units** based on the language of particle physics
 - quantum mechanics the unit of action $\hbar = 1.0545718 \times 10^{-34} \text{ kg m}^2 \text{ s}^{-1}$
 - relativity the speed of light $c = 299\,792\,458 \text{ m s}^{-1}$
 - particle physics unit of energy $1 \text{ GeV} = 1.60218 \times 10^{-10} \text{ J (or kg m}^2 \text{ s}^{-2})$
 - Units become (i.e. with the correct dimensions):
 - Energy GeV Time $(\text{GeV}/\hbar)^{-1}$ [today's lecture lasts $8.2 \times 10^{27} \hbar/\text{GeV}$]
 - Momentum GeV/c Length $(\text{GeV}/\hbar c)^{-1}$
 - Mass GeV/c² Area $(\text{GeV}/\hbar c)^{-2}$
 - Simplify by setting $\hbar = c = 1$. Need to restore factors of \hbar and c depending on the quantity.
 - Energy GeV Time GeV⁻¹
 - Momentum GeV Length GeV⁻¹
 - Mass GeV Area GeV⁻²
 - From the cookbook: $\hbar c = 197.3 \text{ MeV fm}$ and $(\hbar c)^2 = 0.3894 \text{ GeV}^2 \text{ mb}$ where $1 \text{ b} = 100 \text{ fm}^2 = 10^{-28} \text{ m}^2$, $1 \text{ mb} = 10^{-27} \text{ cm}^2$

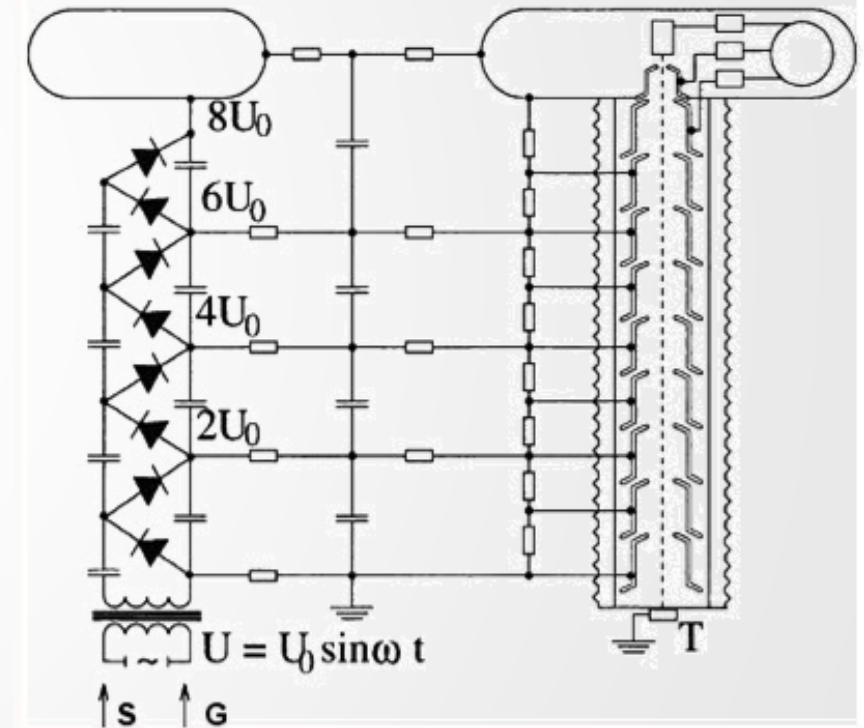
I.3 ELECTROSTATIC FORCE

Images: Wikipedia

- Van **de Graaff generator** uses electrostatic generator (rubber band) to accumulate electric charge on conducting sphere
 - up to 2 MeV in the 1930s, (nowadays 5 MeV when operated in air, up to 20 MeV in gas)
 - limited by corona discharge at sharp edges and by the leakage current
 - The **Cockcroft-Walton generator** uses an alternating voltage source, a transformer and a voltage multiplier
 - First 'Kernzertümmerung' in 1930
- ${}^7\text{Li} + \text{p} \rightarrow {}^4\text{He} + {}^4\text{He} + 17,35 \text{ MeV}$
- The acceleration principle is also used for linear accelerators



Cockcroft-Walton generator



linear electrostatic accelerator

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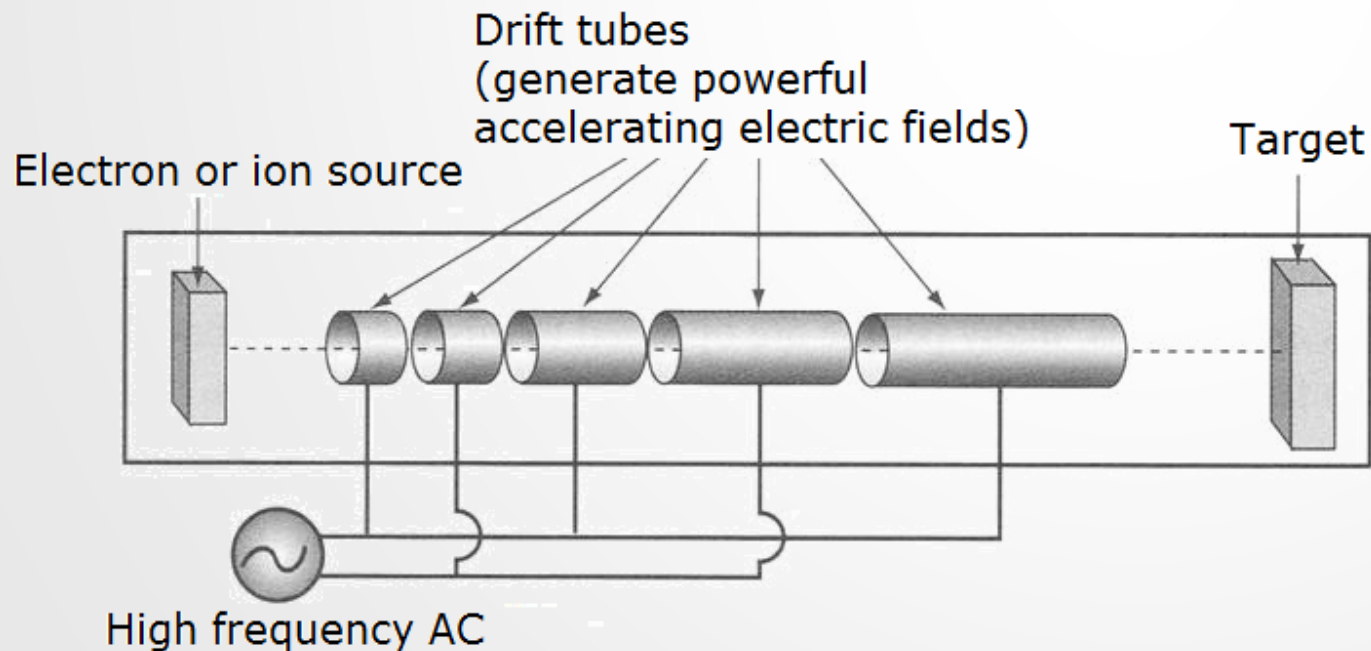
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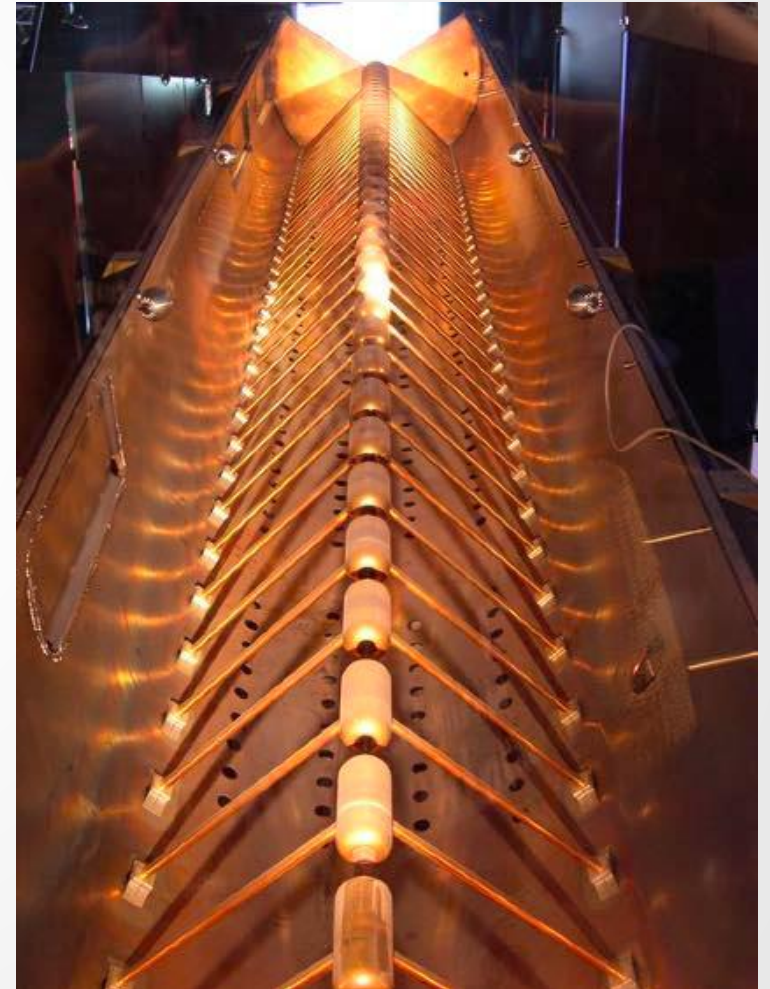
2. ENABLING CONCEPTS

2.1 LINEAR ACCELERATORS (ELECTRODYNAMIC)

- Drive successive drift tubes with varying lengths (Widerö – Alvarez structure) with appropriate high power HF source
- Lengths compensate for acceleration
- Advantage: Need **no high voltages**, only **one frequency**
- Disadvantage: Particles don't come back



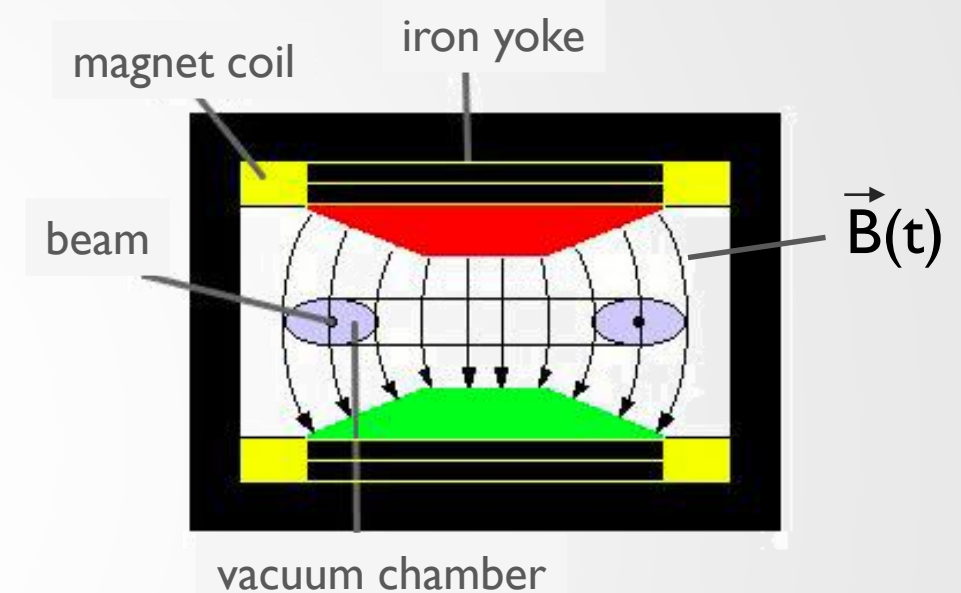
CERN 'Microcosm'



2.2 BETATRON

Images: Wikipedia

- In reference to 'Beta' rays, fast moving electrons
- Electrons are injected into a **doughnut shaped vacuum** chamber that is the secondary coil of a **transformer** operating at several hundred Hz → oscillating field
- Injection is timed to the rising edge of **the magnetic field**
 1. The **changing magnetic field** induces an **azimuthal electric** field tangent to the electron path: $\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$
 2. The increasing magnetic field keeps the electrons on circular orbits. Quasi-stable orbits are possible.
- When the B-field has reached its maximum value, the electrons are extracted



6 MeV Betatron,
Germany, 1942-46
(Wikipedia)

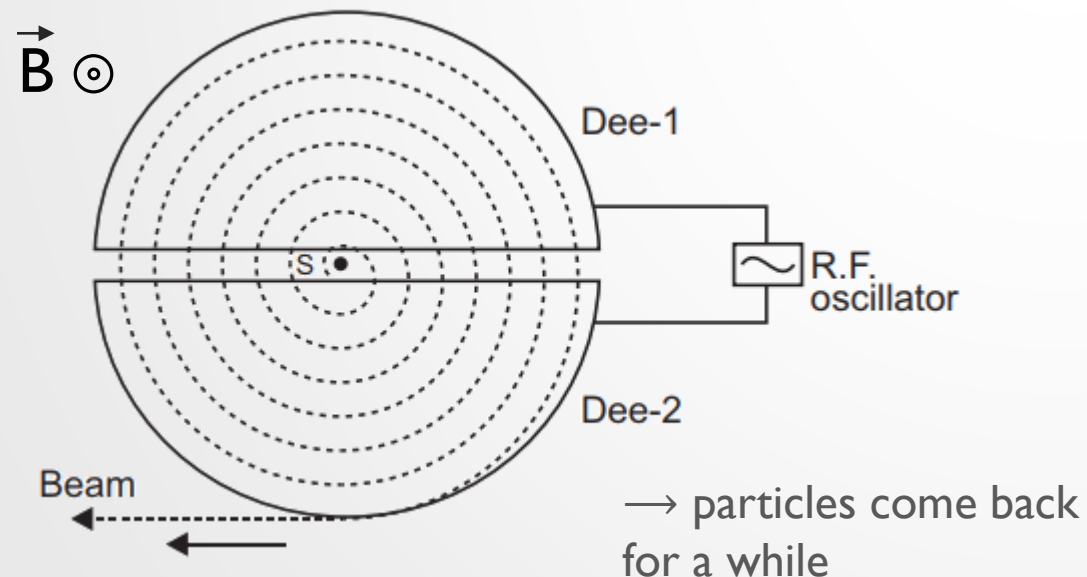
2.3 CYCLOTRON

Images: Wikipedia

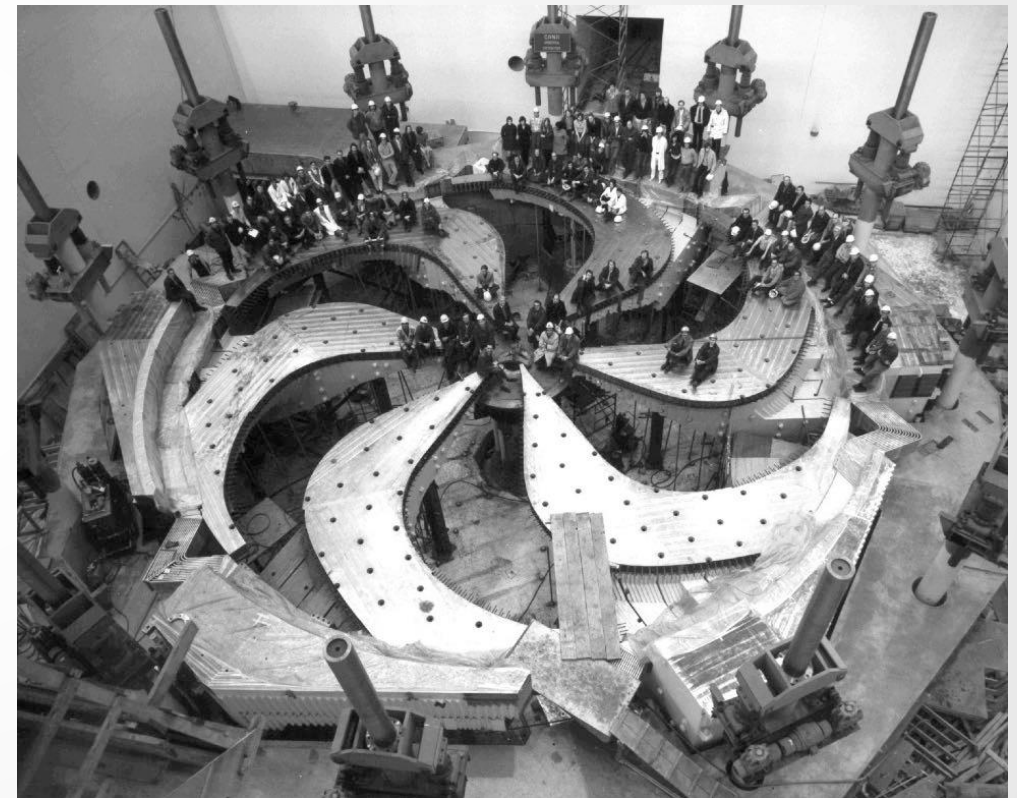
- Ion/particle source 'S' in the center of a disk
- 'Dee' segments are on oscillating potential with **cyclotron frequency ω_c** which is a function of q , m and of the strength of the **perpendicular magnetic field B**

$$\frac{mv^2}{r} = qvB \rightarrow \frac{v}{r} = \omega_c = \frac{qB}{m} \rightarrow \frac{qB}{m\gamma}$$

- for non-relativistic speeds, no modulation needed!



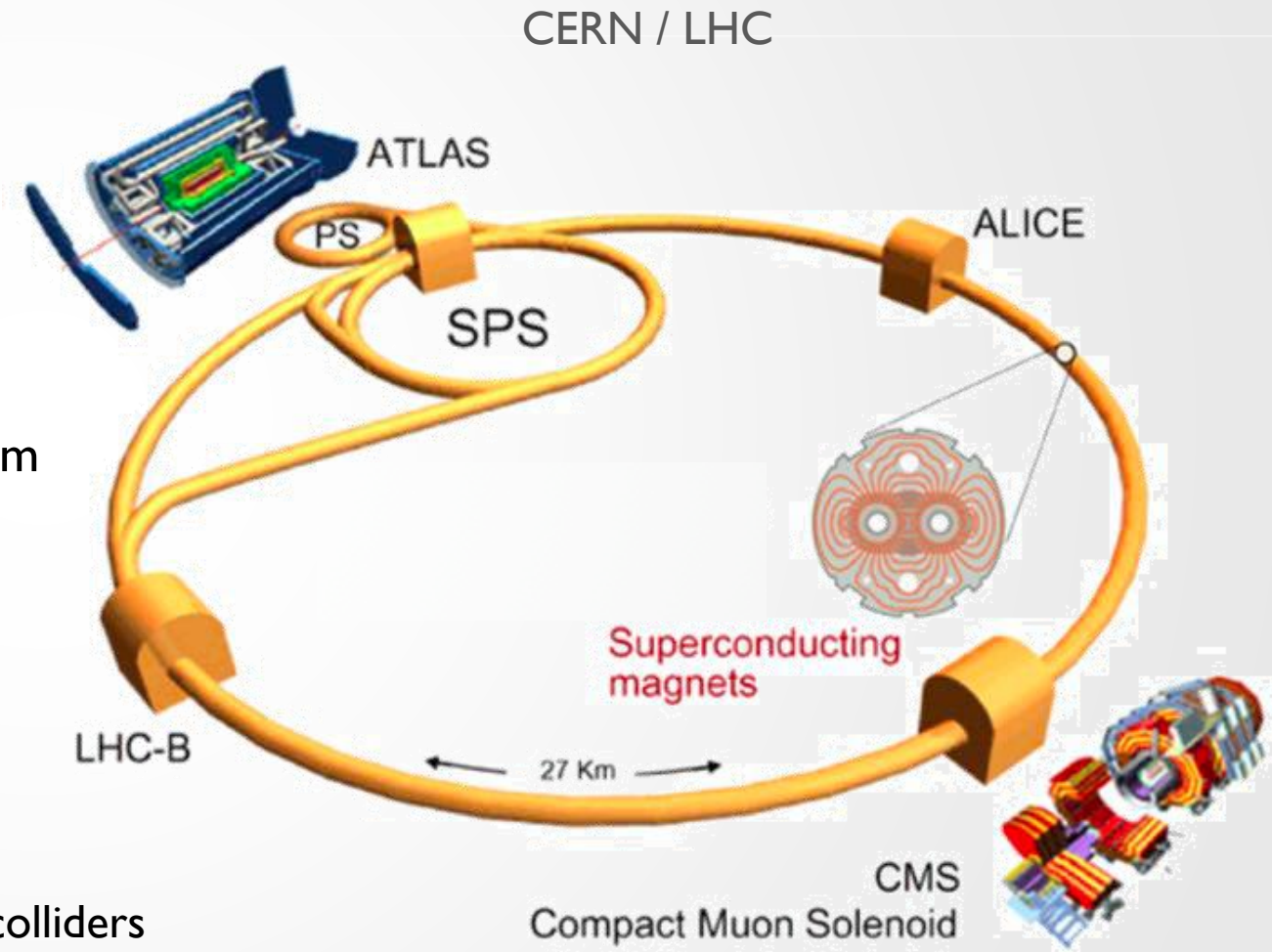
World's biggest cyclotron:
TRIUMF, Vancouver, Canada
 H^- ions, 520 MeV p, $\beta=0.75$



The segmented magnets provide a B-field grows with radius and compensates the γ^{-1} factor, thus stabilizing the relativistic cyclotron trajectory

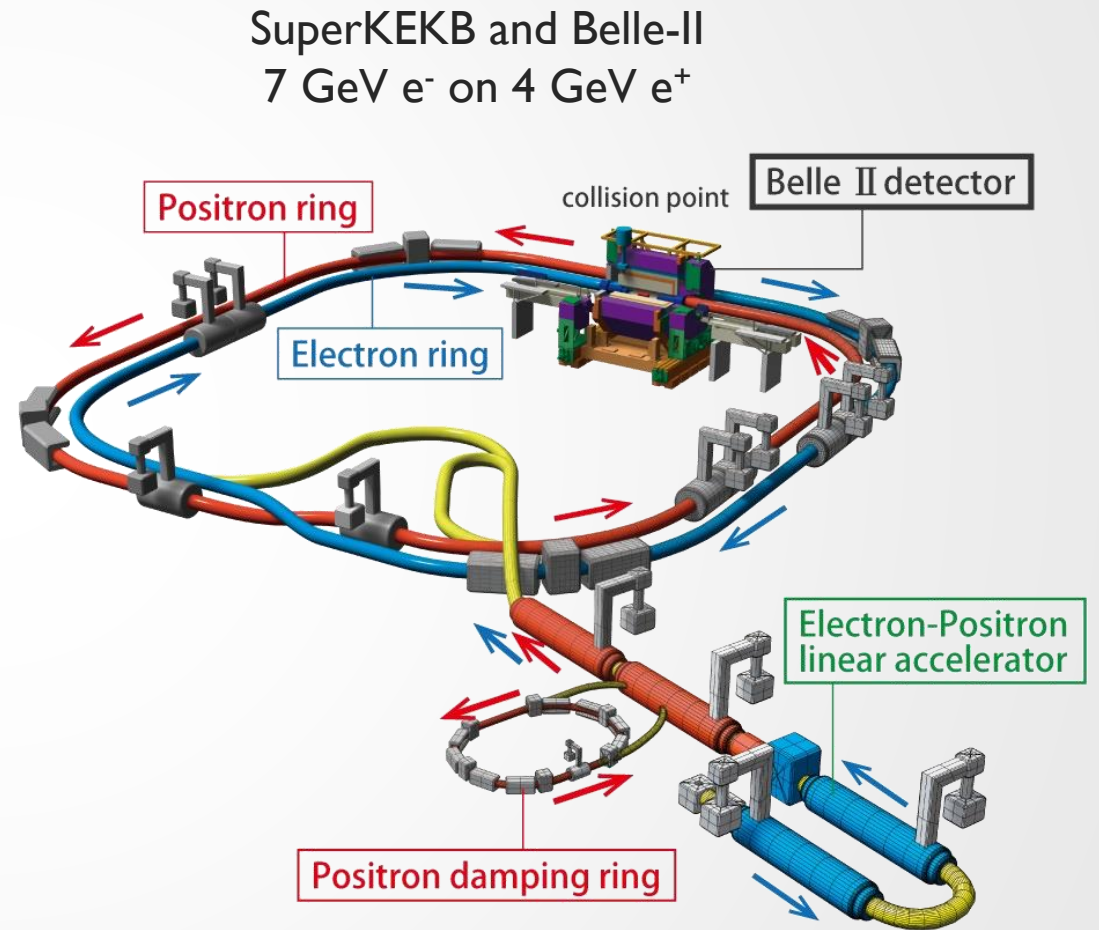
2.4 SYNCHROTRON / STORAGE RING / COLLIDER

- Magnets keep particles on circular orbits
 - Dipole magnets bend the trajectory
 - Quadrupole magnets focus the beam
- Acceleration by RF cavities
 - Klystrons power the RF cavities
- need pre-accelerator complex and injection system
- beam-dump / extraction system
- Advantage: particles come back
- main limitations of the achievable energy
 - synchrotron radiation for e^+/e^- storage rings
 - magnetic field of the dipole moments for hadron colliders



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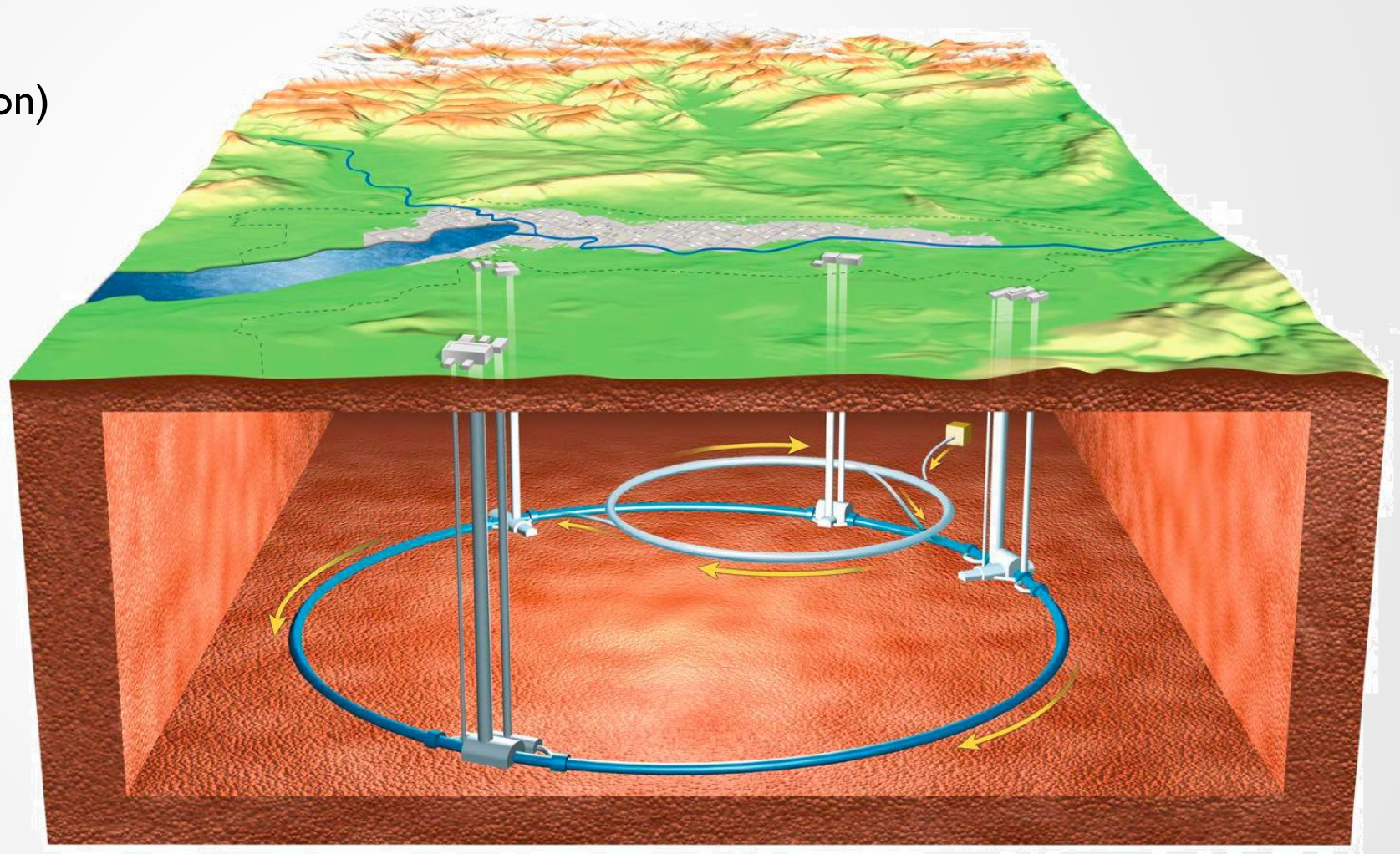
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$$\sqrt{s} = m_{\Upsilon(4S)} = 10.57 \text{ GeV}$$

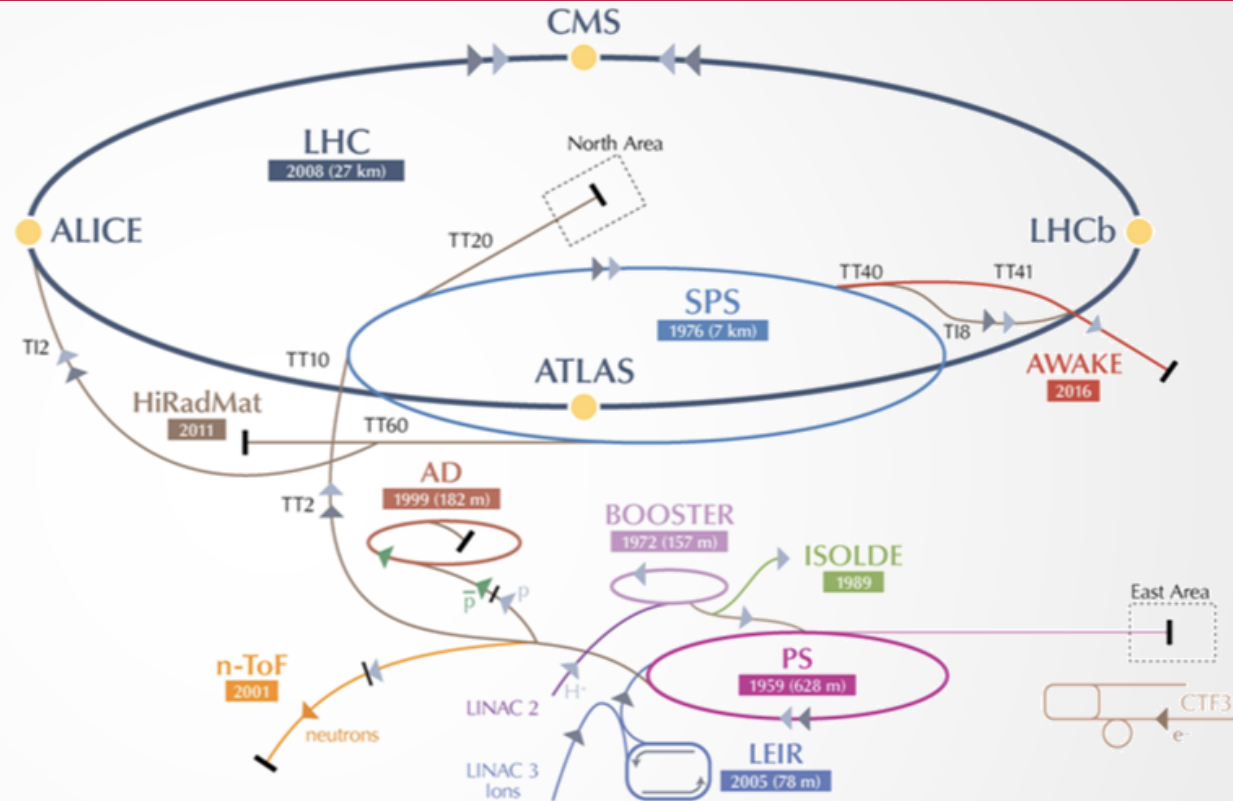
2.5 LHC ACCELERATOR COMPLEX

- 100-150m underground
- two circulating proton (or ion) beams
- 4 main interaction points instrumented by the main experiments:
 - CMS
 - ATLAS
 - LHCb
 - Alice



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▶ p (proton) ▶ ion ▶ neutrons ▶ \bar{p} (antiproton) ▶ electron ▶ \leftrightarrow proton/antiproton conversion

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility AWAKE Advanced WAKEfield Experiment ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINEar ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

3.THE ENERGY FRONTIER

3.1 POWER DISSIPATION OF AN ACCELERATED CHARGE



- For a charge q at rest, Coulomb's law states

$$\phi(r) = \frac{1}{4\pi\epsilon_0} \frac{q}{r} \rightarrow \vec{E} = -\vec{\nabla}\phi = \frac{q}{4\pi\epsilon_0} \frac{\vec{r}}{r^3}$$

- Consider a short period Δt of acceleration to a non-relativistic speed of Δv

- The E-field will have a parallel component inside a sphere of radius ct

$$\frac{E_{\perp}}{E_{\parallel}} = \frac{\Delta v t \sin \theta}{c \Delta t}$$

- With $t = r/c$ this becomes $E_{\perp} = \frac{q}{4\pi\epsilon_0 r^2} \frac{\Delta v}{\Delta t} \frac{r \sin \theta}{c} = \frac{q \dot{v} \sin \theta}{4\pi\epsilon_0 r c^2}$

- The local energy flux density is described by the Poynting vector

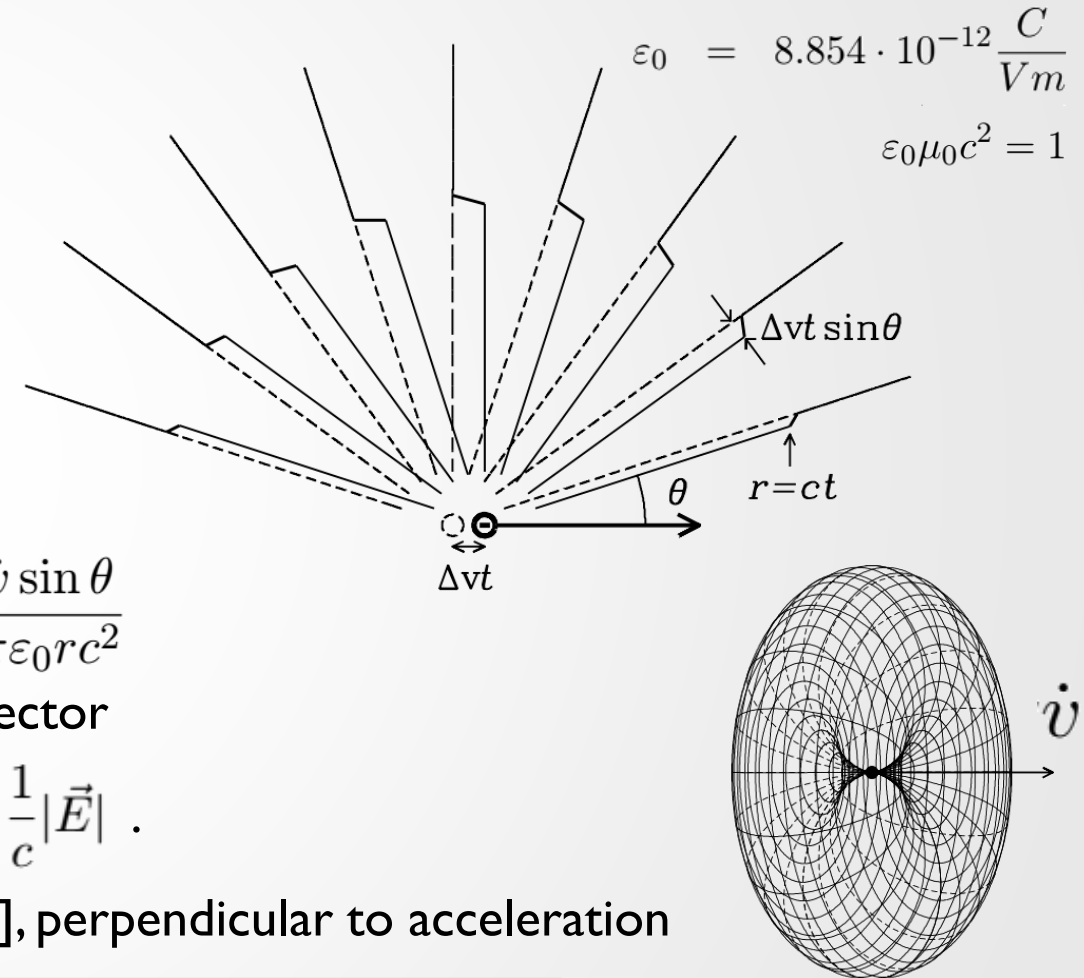
$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B} = \vec{e}_r \frac{q^2 \dot{v}^2 \sin^2 \theta}{16\pi^2 c^3 \epsilon_0 r^2} \text{ where we've used } |\vec{B}| = \frac{1}{c} |\vec{E}|.$$

- There is a 'doughnut' angular pattern [same as Hertz dipole], perpendicular to acceleration

Total power:

$$P = \int d\Omega \vec{S} \cdot \vec{e}_r = \frac{q^2 \dot{v}^2}{16\pi^2 c^3 \epsilon_0 r^2} \int_0^{2\pi} r d\phi \int_0^{\pi} r \sin^3 \theta d\theta = \frac{q^2 \dot{v}^2}{6\pi \epsilon_0 c^3}$$

Larmor's equation



3.1 POWER DISSIPATION OF AN ACCELERATED CHARGE

[3]

- Because energy E and time t transform the same way $E' = \gamma E$, $t' = \gamma t$, the power P is a Lorentz scalar. Hence, the invariant form of Larmor's equation is

$$P = \frac{q^2}{6\pi\epsilon_0 m^2 c^3} \left(\frac{dp}{dt} \right)^2 \rightarrow P = -\frac{q^2 c}{6\pi\epsilon_0 (mc^2)^2} \frac{dp^\mu}{d\tau} \frac{dp_\mu}{d\tau} = \frac{q^2 c}{6\pi\epsilon_0 (mc^2)^2} \left(\left(\frac{d\vec{p}}{d\tau} \right)^2 - \frac{1}{c^2} \left(\frac{dE}{d\tau} \right)^2 \right)$$

- This is valid in every reference frame and $dt = \gamma d\tau$.
- Linear acceleration:** We can differentiate $E^2 = (mc^2)^2 + \vec{p}^2 c^2 \rightarrow E \frac{dE}{d\tau} = c^2 \vec{p} \cdot \frac{d\vec{p}}{d\tau}$ and use $E = \gamma mc^2$, $\vec{p} = \gamma m \vec{v}$ to write $\frac{dE}{d\tau} = \vec{v} \frac{d\vec{p}}{d\tau}$.

typical gradient of a linear accelerator:

We find:

$$P = \frac{q^2 c}{6\pi\epsilon_0 (mc^2)^2} \left(\frac{d\vec{p}}{dt} \right)^2 = \frac{q^2 c}{6\pi\epsilon_0 (mc^2)^2} \left(\frac{dE}{dx} \right)^2 \quad \text{e.g.} \quad \frac{dE}{dx} = 25 \text{ MeV m}^{-1} \rightarrow P = 1.1 \cdot 10^{-16} \text{ W}$$

- The energy efficiency for linear acceleration is negligible:

$$\eta = \frac{P}{dE/dt} = \frac{P}{v dE/dx} = \frac{q^2}{6\pi\epsilon_0 (mc^2)^2} \frac{1}{\beta} \frac{dE}{dx} \sim 10^{-13}$$

(electrons: $m_e = 9.11 \cdot 10^{-31} \text{ kg}$, $q=e=1.602 \cdot 10^{-19} \text{ C}$, $\epsilon_0 = 8.854 \cdot 10^{-12} \text{ C/Vm}$)

3.2 SYNCHROTRON RADIATION

- Circular motion does not change the energy $\frac{dE}{dt} = 0$,
 and $\frac{dp}{dt} = \omega p = \frac{v}{R}p \approx \frac{c}{R}p = \frac{E}{R}$ where the approximation holds for ultra-relativistic particles. Inserting this gives

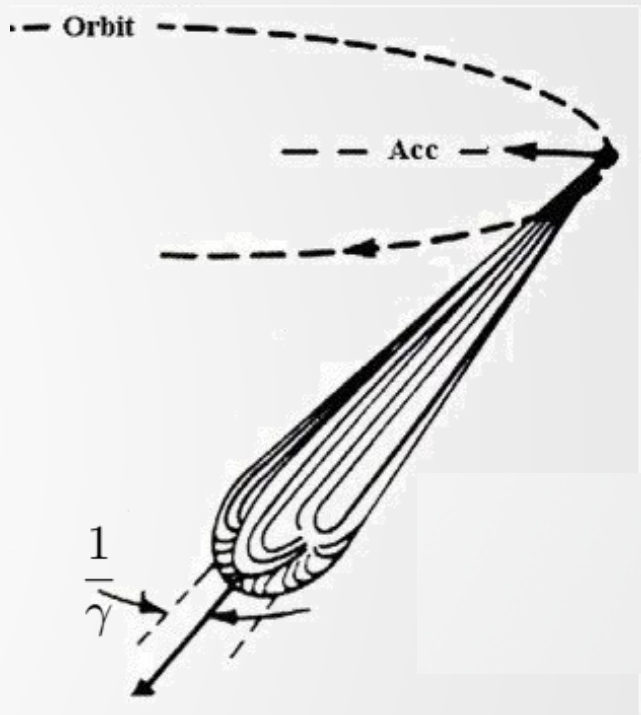
$$P = \frac{q^2 c}{6\pi\epsilon_0} \frac{\gamma^2}{(mc^2)^2} \left(\frac{d\vec{p}}{dt}\right)^2 = \frac{q^2 c}{6\pi\epsilon_0} \frac{(E/(mc^2))^2}{(mc^2)^2} \frac{E^2}{R^2} = \frac{q^2 c}{6\pi\epsilon_0} \frac{1}{(mc^2)^4} \frac{E^4}{R^2}$$

and 4th power has dramatic consequences: $\left(\frac{m_p}{m_e}\right)^4 \approx 1836^4 \approx 1.1 \cdot 10^{14}$

- Moreover, for a given P, $E_{\text{max}} \propto \sqrt{R}$, effectively limiting the feasibility of circular high energy e^\pm colliders.

- The angle transforms as $\tan \theta = \frac{\sin \theta'}{\gamma(\cos \theta' + \beta)}$

and therefore the doughnut becomes collimated to γ^{-1} .



	$E_{\text{loss}}/\text{turn}$	damping
p in LHC, 7 TeV	7 keV	1.5 days
e^\pm in LEP-II, 104.5 GeV	3 GeV	18 ms
70 GeV	700 keV	

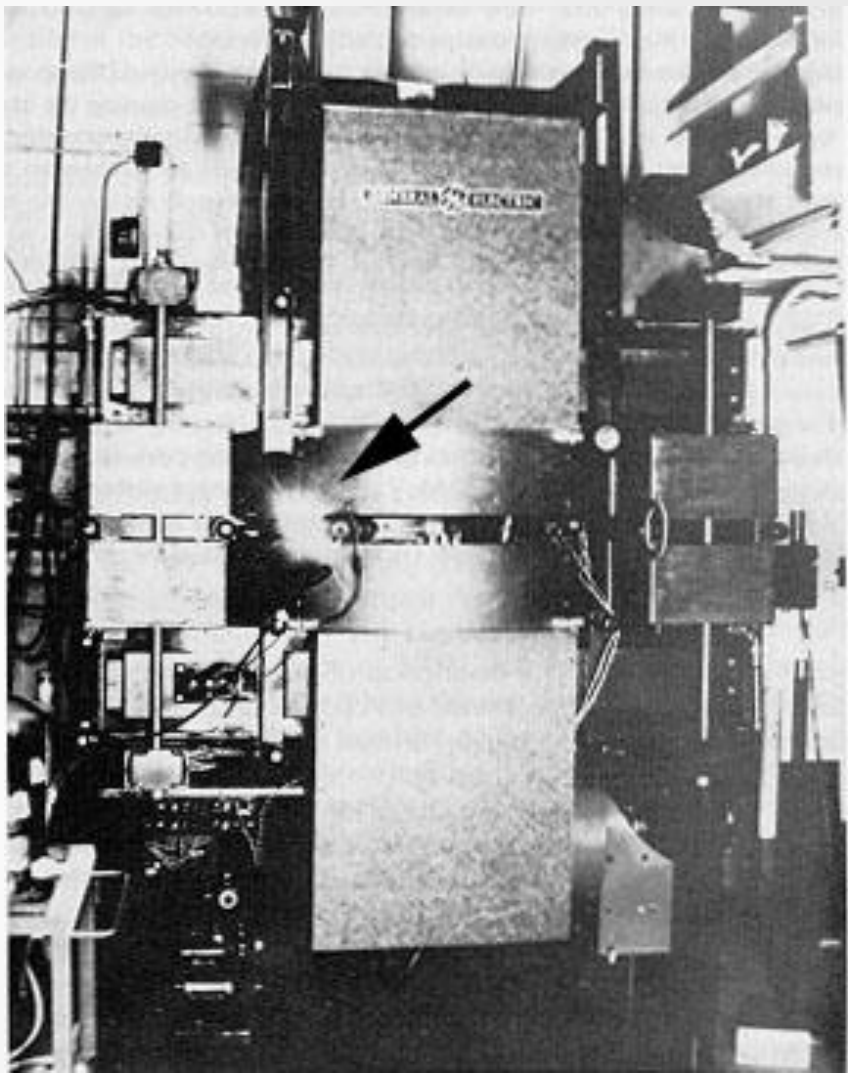
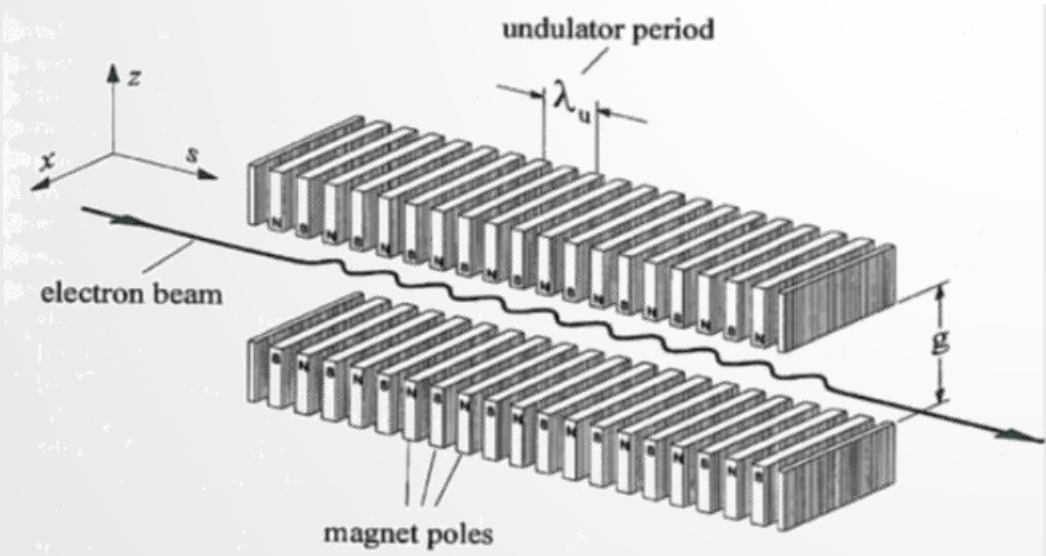
3.3 SYNCHROTRON RADIATION

Images:Wikipedia

synchrotron radiation at accelerators:

accelerator	L [m]	E [GeV]	R [m]	B [T]	ΔE [keV]
BESSY I (Berlin)	62.4	0.80	1.78	1.50	20.3
DELTA (Dortmund)	115	1.50	3.34	1.50	134.1
DORIS II (Hamburg)	288	5.00	12.2	1.37	4.53×10^3
ESRF (Grenoble)	844	6.00	23.4	0.855	4.90×10^3
PETRA (Hamburg)	2304	23.50	195	0.40	1.38×10^5
LEP (Geneva)	27×10^3	70.00	3000	0.078	7.08×10^5

‘Undulator’ schematic of industrial synchrotron sources

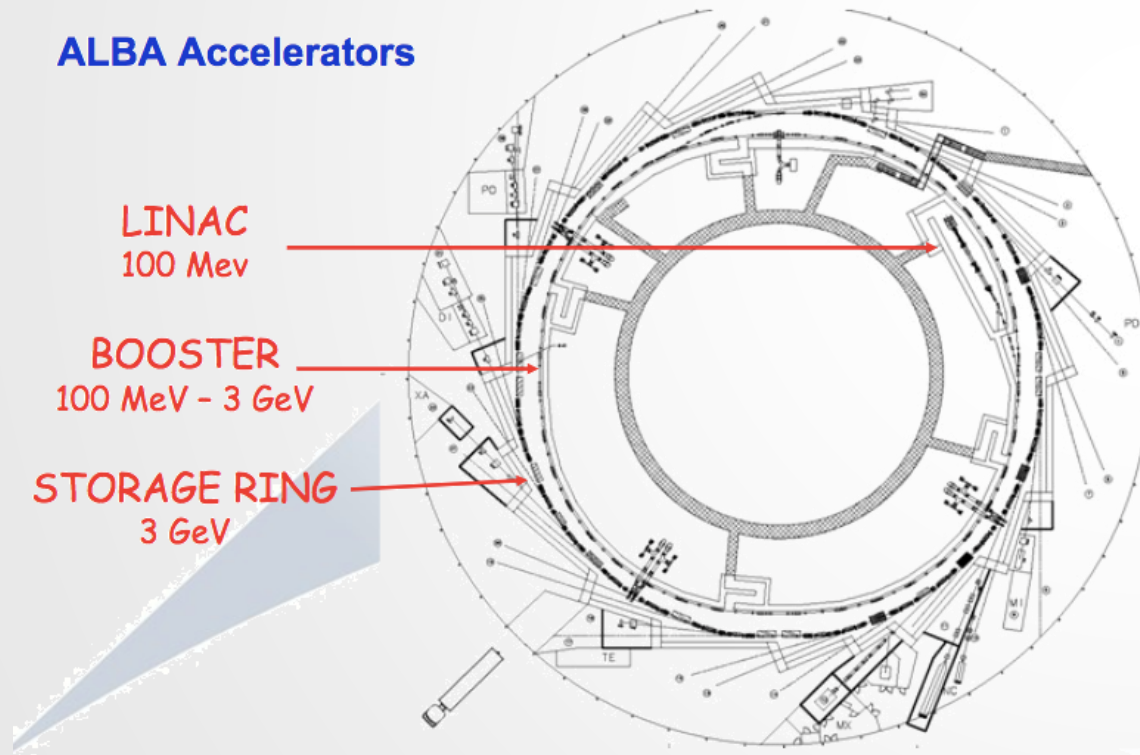


General electric synchrotron accelerator, 1946

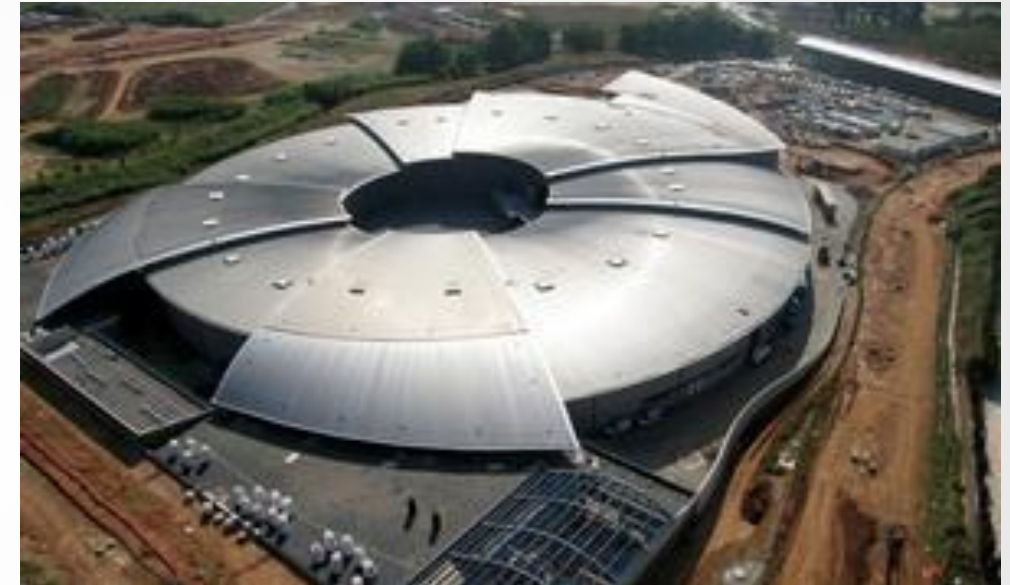
3.3 SYNCHROTRON RADIATION FOR SCIENCE

- Many commercial & scientific synchrotrons
https://en.wikipedia.org/wiki/List_of_synchrotron_radiation_facilities
- Example:ALBA synchrotron in Barcelona:
3 GeV storage ring with 270m circumference

ALBA Accelerators



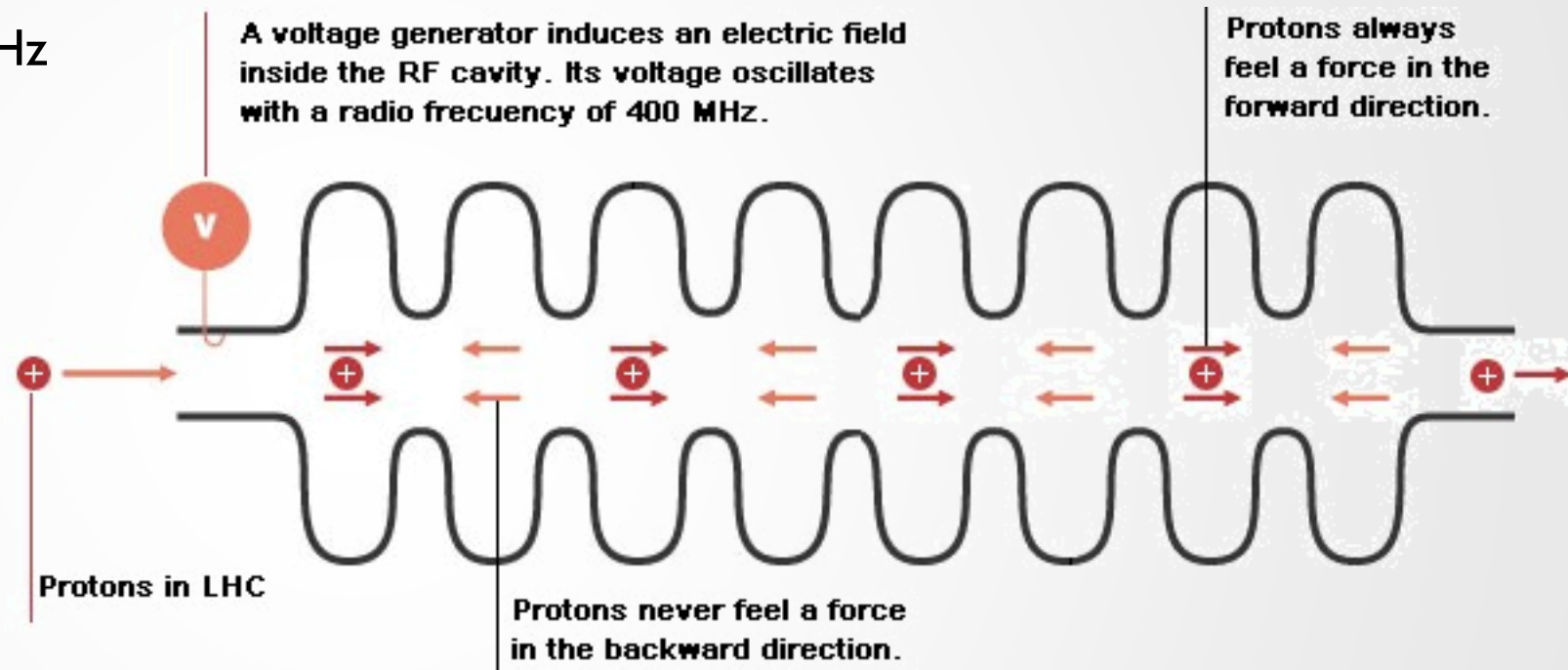
The ALBA synchrotron near Barcelona



- X-ray microscopy
- Powder diffraction
- X-ray absorption
- IR micro-spectroscopy
- Molecular crystallography
- Small and wide angle scattering
- Photoemission
- X-ray magnetic dichroism

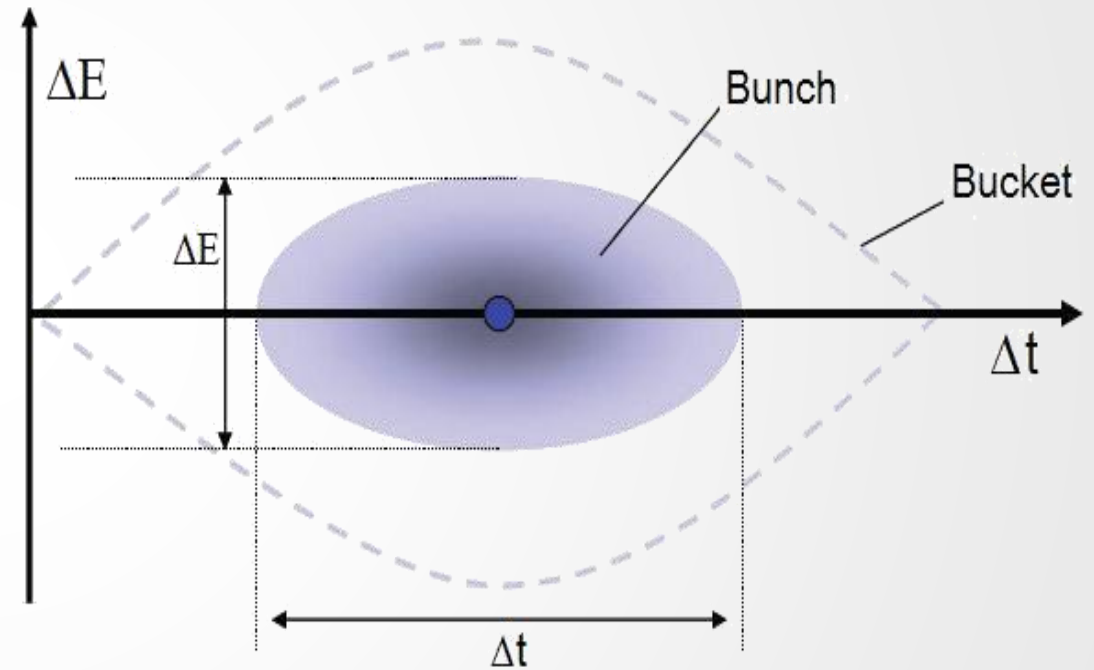
3.4 ACCELERATION: RADIO-FREQUENCY CAVITIES

- There are 2808 bunches in the LHC
- LHC RF cavities operate at 400 MHz ($\lambda \approx 70$ cm) providing 16 MeV/turn or 180 GeV/s.
- The oscillating wave in the cavities stabilizes the bunch structure
- cavities are powered by Klystrons: 8x300kW!
- feedback loop for beam control
- Both, KEKB (4 TW stored energy) and LHC (13 TW) use superconducting cavities



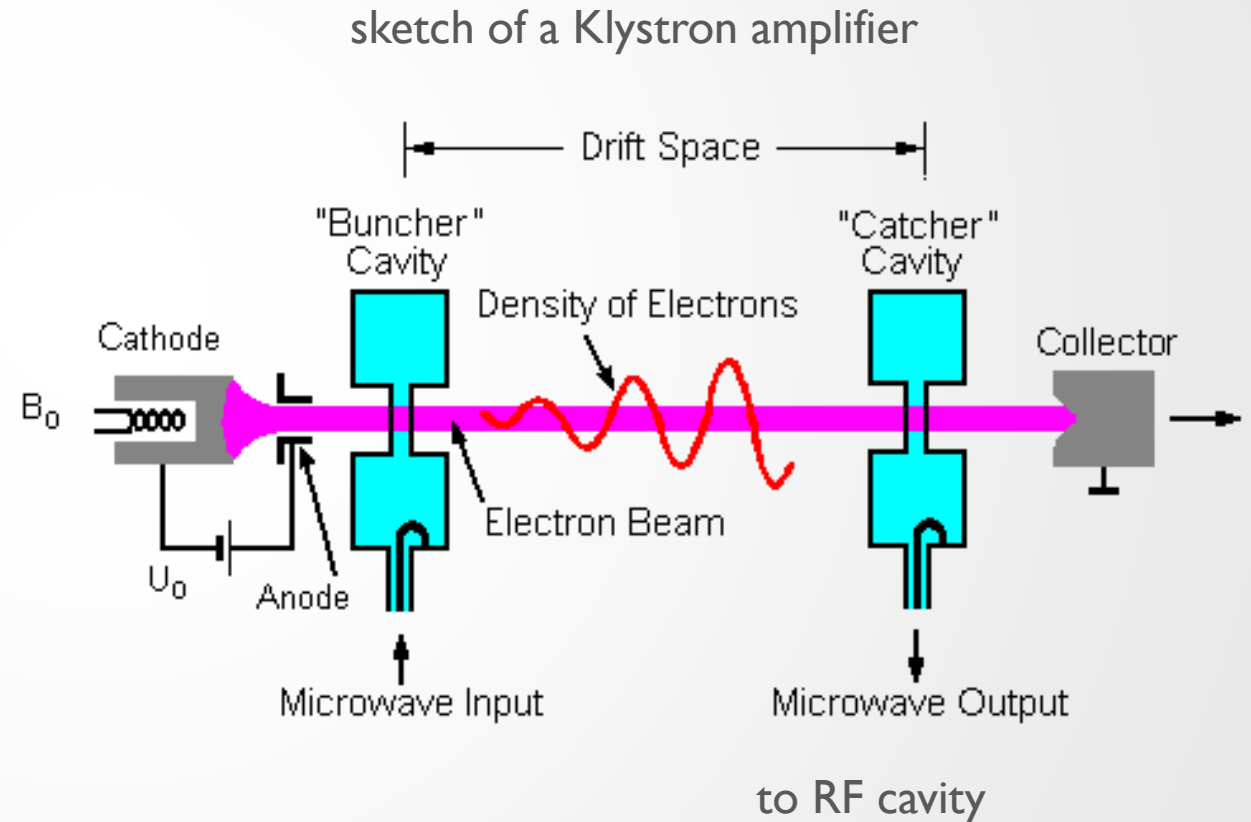
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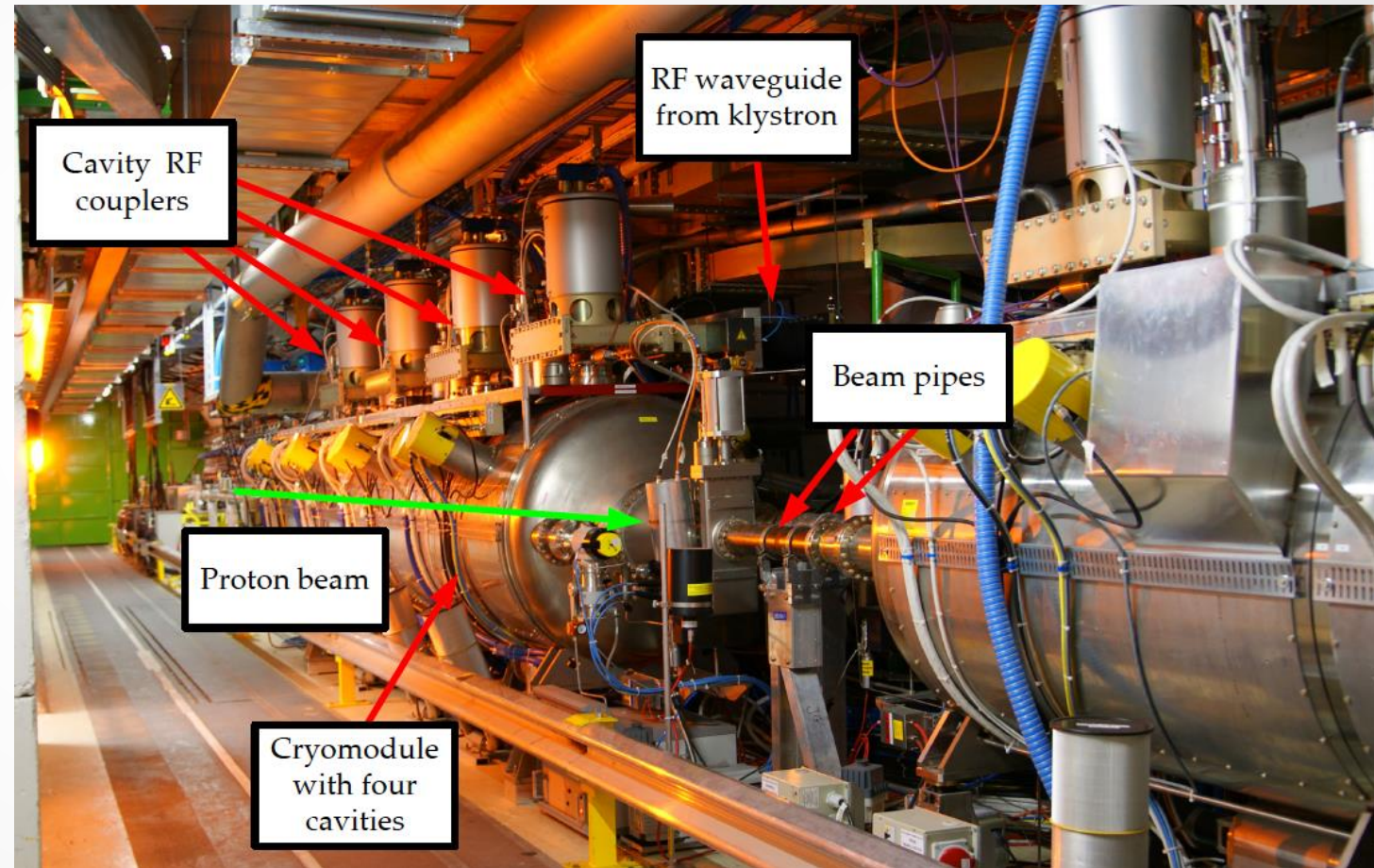
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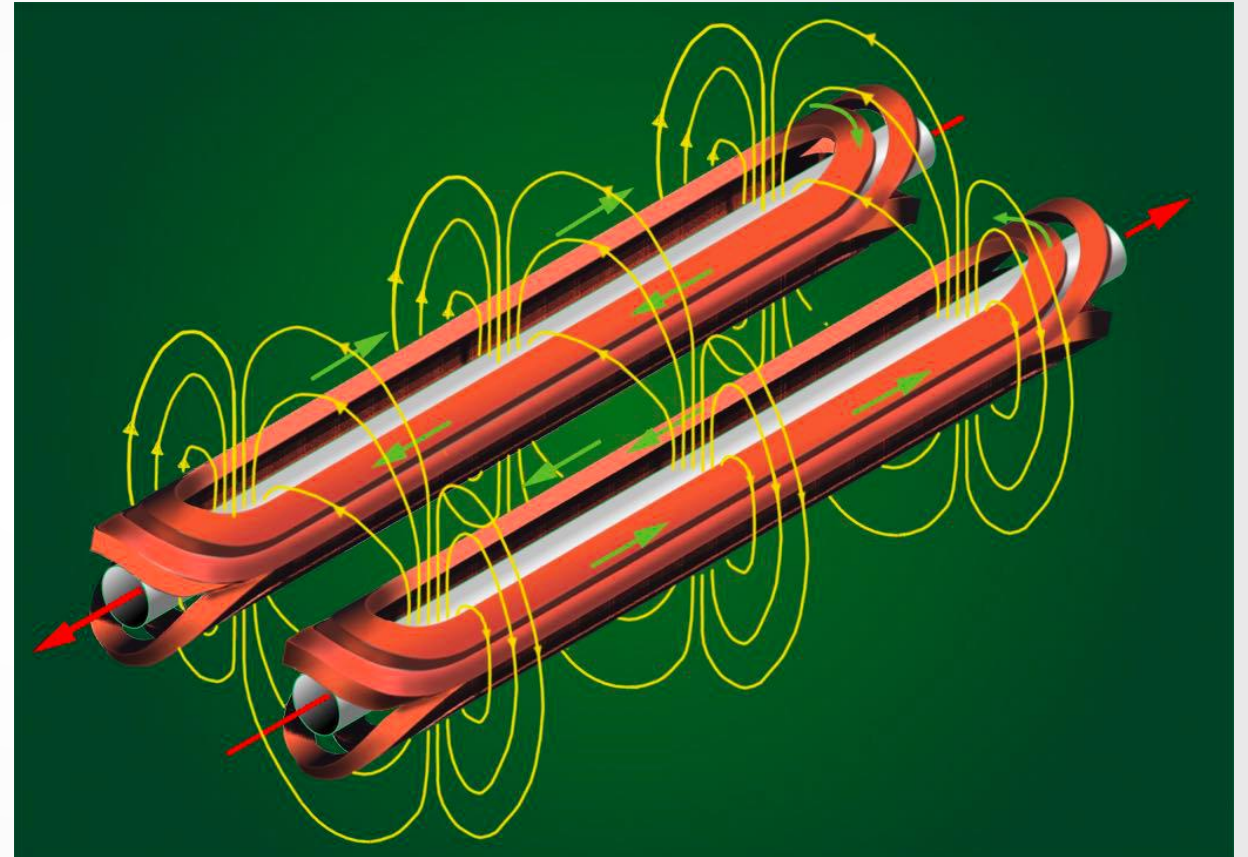
3.5 LHC MAGNETS

- limiting factor of LHC pp collision energy
- 1232 magnets operated at 8.33 T and 1.9K
- 15m length, cooled with suprafluid Helium

$$|\vec{F}| = |q \vec{v} \times \vec{B}| \stackrel{!}{=} \left| \frac{d\vec{p}}{dt} \right| = \omega p = \frac{v}{\rho} p \rightarrow B = \frac{p}{q\rho}$$

or $p = q \rho B$.

- bending radius (Larmor radius) is $\rho = 2804$ m
- with $p = 7$ TeV/c and $q=e$ it follows $B = 8.33$ T
- Two coils needed for counter-circular motion
- Collision of Pb ions:
 - $p_{\text{ion}} = B Z q \rho = A p_{\text{nucleon}}$
 - $p_{\text{nucleon}} = 7\text{TeV} \cdot 82/208 = 1.38$ TeV. $p_{\text{ion}} = 574$ TeV!



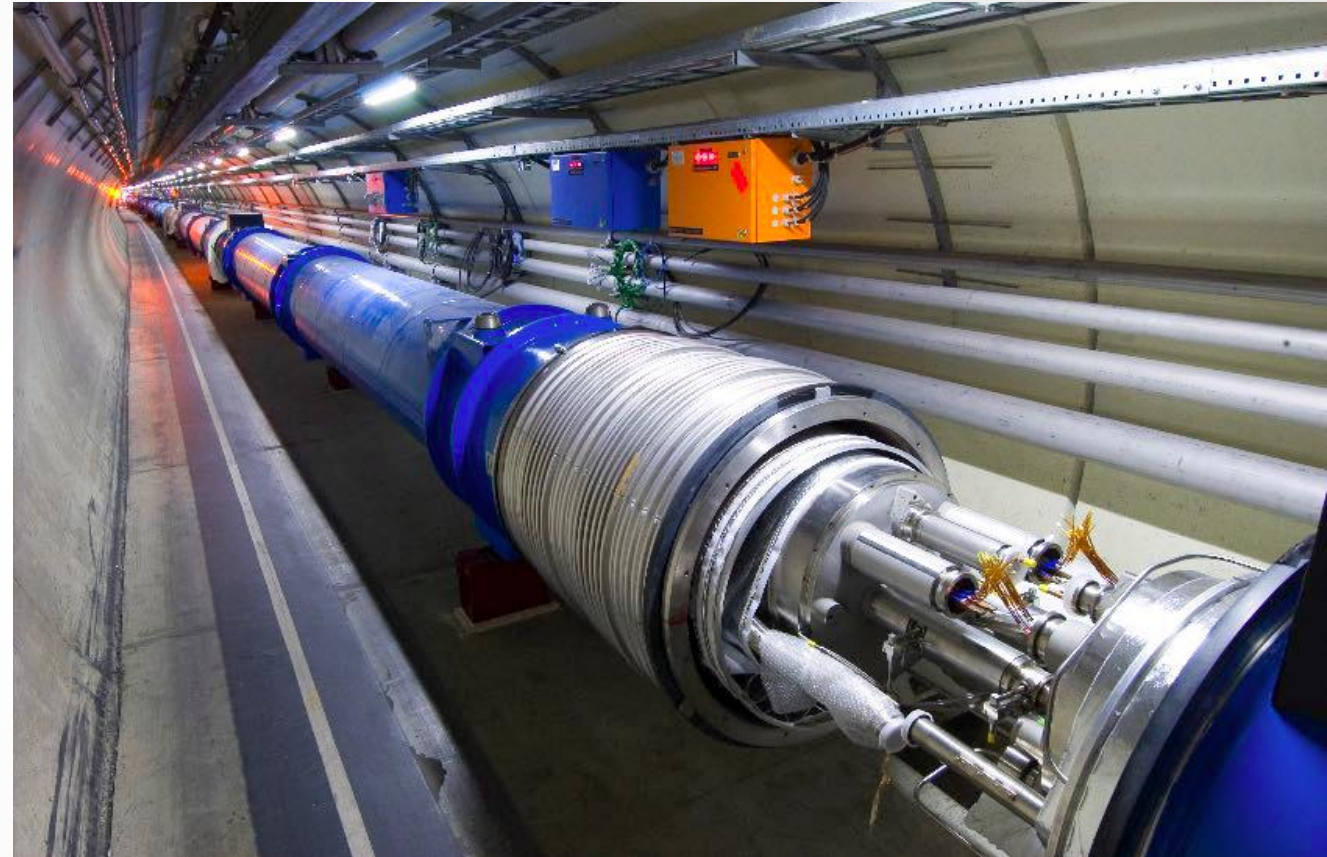
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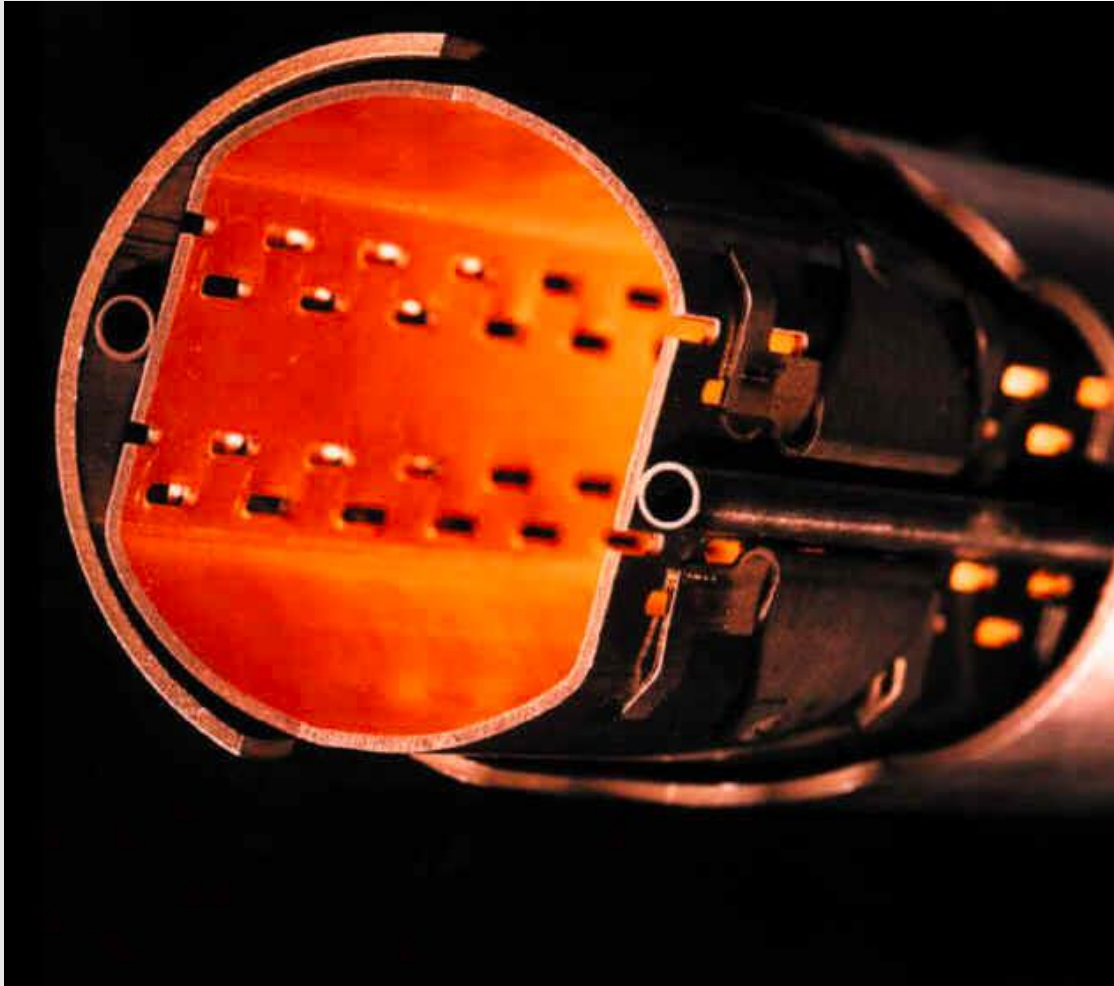
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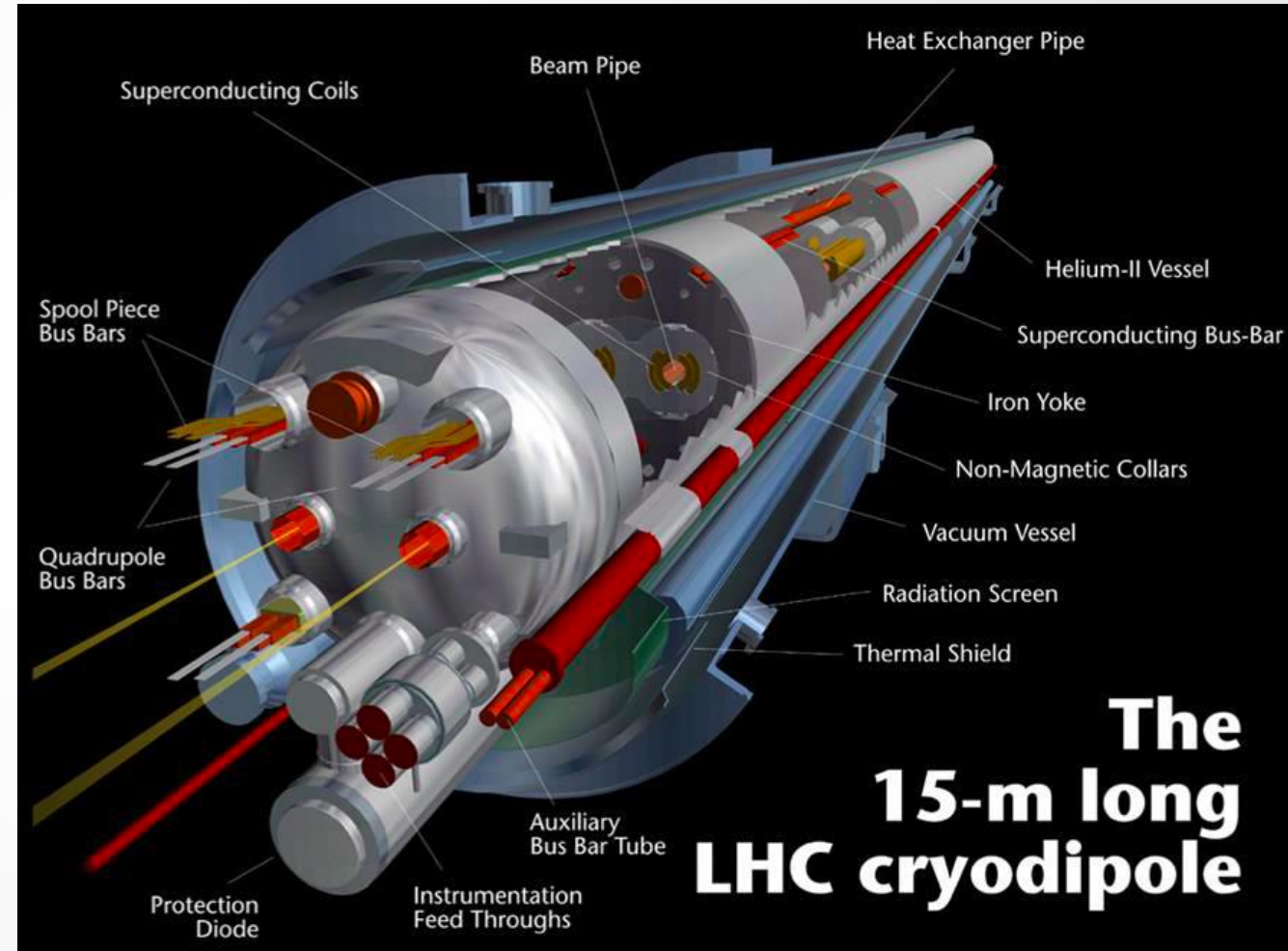
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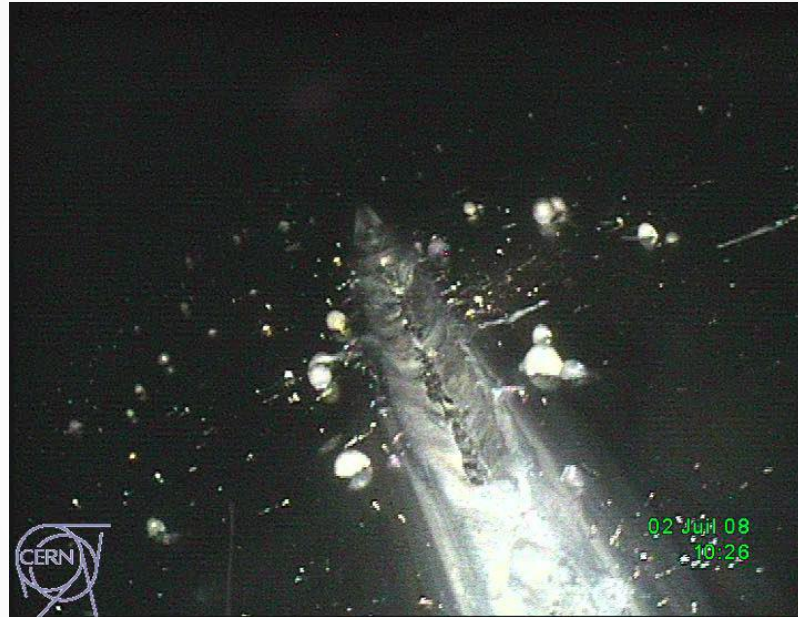
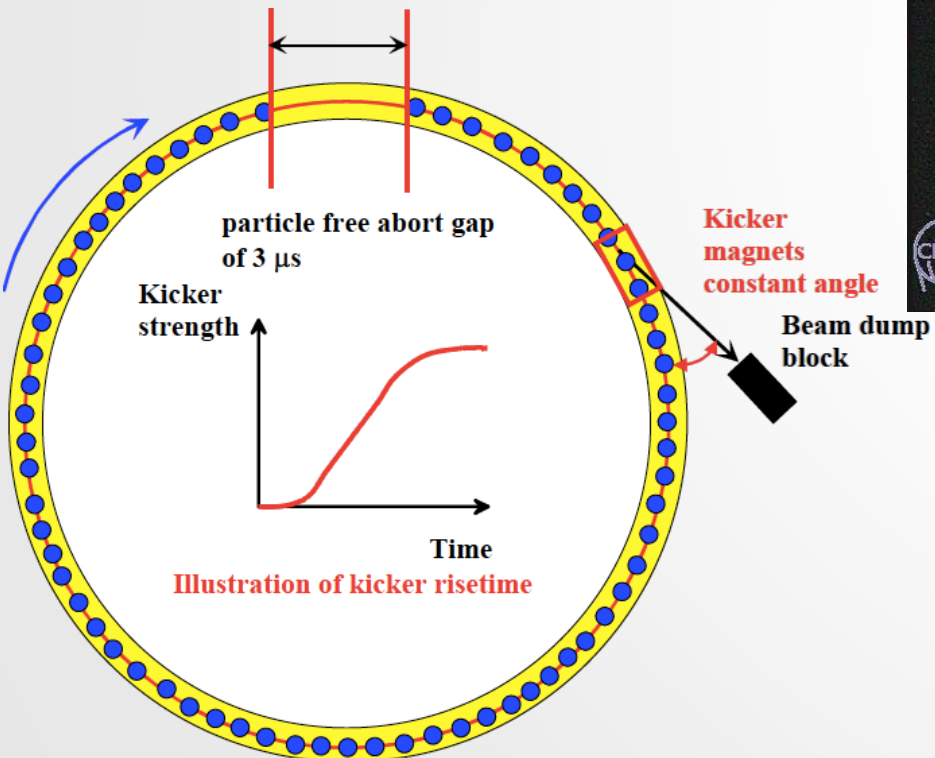
LHC beam screen in dipole magnets:
Shields mirror currents and protects cooling pipes



3.6 LHC BEAM

- LHC beams have each 4 TW power and store 360 MJ/beam

kicker magnet & beam dump system
synced to $3\mu\text{s}$ abort gap

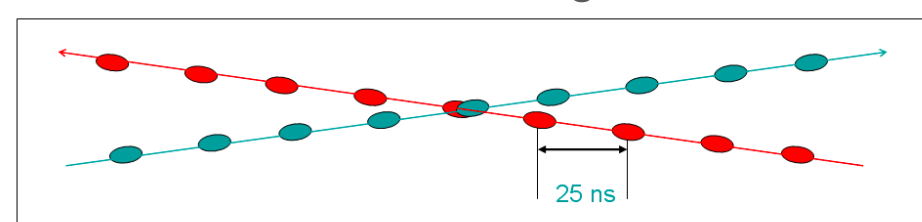


single bunch impact



kicker magnet

schematic of colliding bunches



3.6 LHC BEAM

- Kinetic energy of projectile ~ 300 MJ
- LHC stored energy at design ~ 700 MJ
- Power if that energy is deposited in a single orbit: ≈ 10 TW for $\approx 10^{-4}$ s
 - world energy production is ≈ 13 TW
- 2808 bunches, $115 \cdot 10^9$ p/bunch
- 25 collisions/crossing $\leftrightarrow 40$ MHz



4.THE LUMINOSITY FRONTIER

4.1 FIXED TARGET LUMINOSITY AND CENTRE-OF-MASS ENERGY [4]

- If we shoot a beam of particles with $\Phi = N_{\text{beam}}/\Delta t$ particles per unit time at a fixed target with density ρ and length l per particle, the rate of events is

$$\frac{dN}{dt} = \Phi \rho l \sigma = \mathcal{L} \sigma$$

and the fixed-target luminosity therefore $\mathcal{L} = \Phi \rho l$.

- For ultra-relativistic beam particles, we have

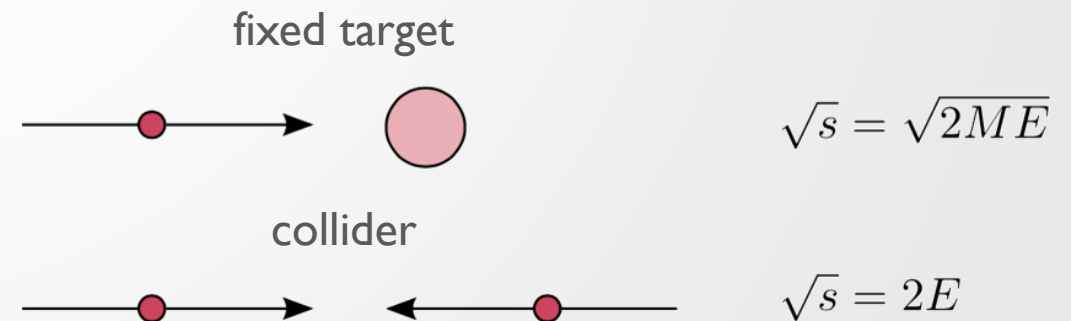
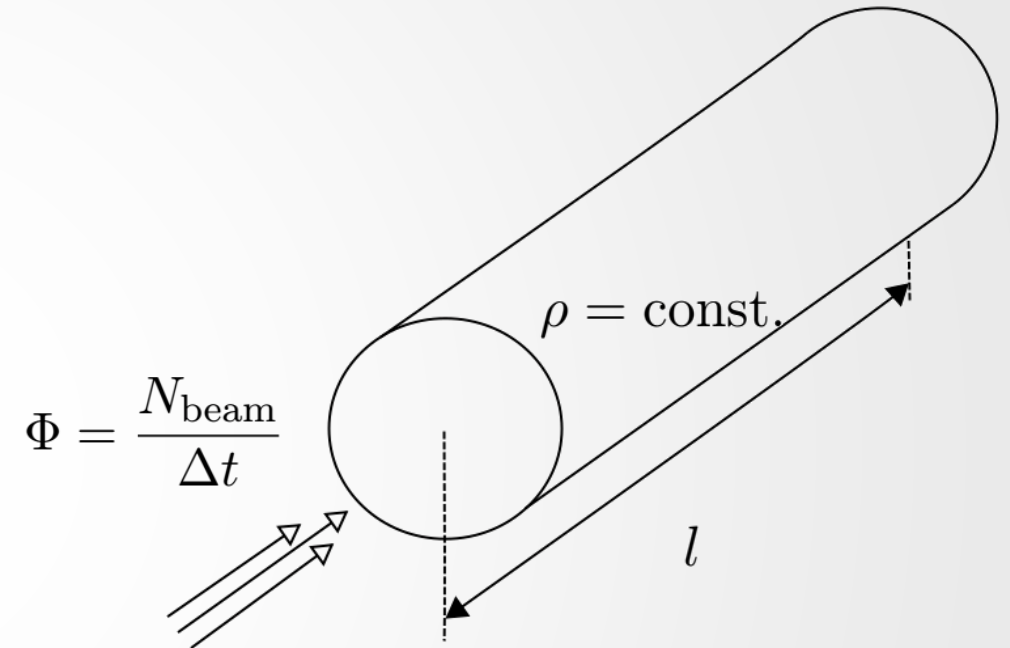
$$p_{\text{beam}}^{\mu} = (E, 0, 0, E)^{\mu}$$

$$p_{\text{target}}^{\mu} = (M, 0, 0, 0)^{\mu}$$

and therefore the centre-of-mass energy is

$$s = (p_{\text{beam}} + p_{\text{target}})^2 = 2EM + M^2.$$

- If $M \ll E$ this simplifies to $\sqrt{s} \approx \sqrt{2EM}$.
- The c.o.m energy of beam-beam collisions with equal energy E is much larger: $\sqrt{s} = 2E$



4.2 BEAM LUMINOSITY

[4]

- For a single bunch crossing, we write

$$\mathcal{L}^{(1b)} = \int dt d^3x \rho_1 \rho_2 |\Delta v_{12}| = 2 \int dx dy ds ds_0 \rho_1(x, y, s, s_0) \rho_2(x, y, s, -s_0)$$

where we've used $s_0 = ct$ and assume independent densities

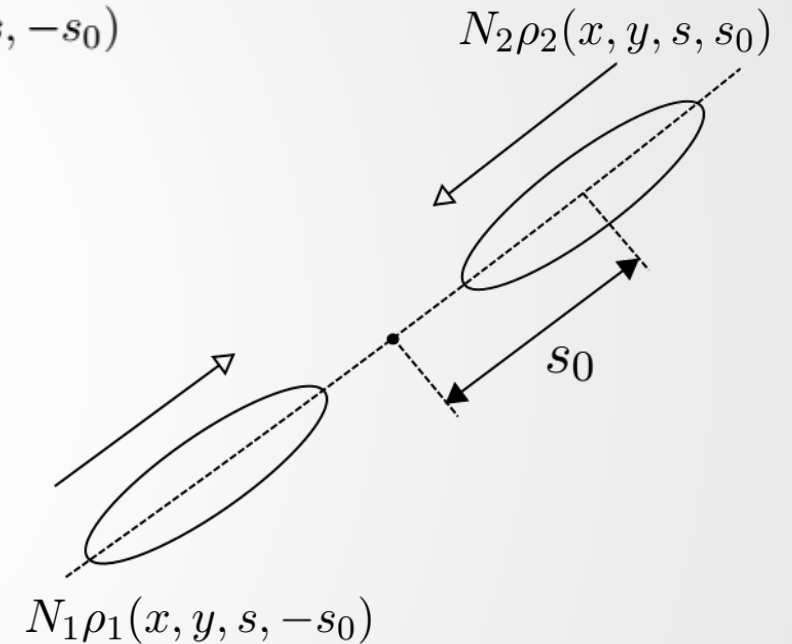
$$\rho_i(x, y, s, \pm s_0) = N_i \rho_{i,x}(x) \rho_{i,y}(y) \rho_{i,z}(s \pm s_0)$$

normalized the number of particles per bunch N_i .

- Assuming Gaussian densities in x, y, z $\rho_x = (\sqrt{2\pi}\sigma_x)^{-1} e^{-\frac{x^2}{2\sigma_x^2}}$ we can calculate the 'instantaneous' luminosity by multiplying with the number of bunches N_b and the revolution frequency f

$$\begin{aligned} \mathcal{L}^{(beams)} &= 2N_b \cdot f \frac{N_1 N_2}{(\sqrt{2\pi})^6 \sigma_x^2 \sigma_y^2 \sigma_z^2} \int dx dy ds ds_0 e^{-\frac{x^2}{\sigma_x^2} - \frac{y^2}{\sigma_y^2} - \frac{s^2 + s_0^2}{\sigma_z^2}} \\ &= \frac{N_1 N_2 f N_b}{4\pi \sigma_x \sigma_y} \end{aligned}$$

where we've used $\int dx e^{-ax^2} = \sqrt{\pi/a}$.



- For the LHC, we have $\sigma_x = \sigma_y = 16.7 \mu\text{m}$, $N_1 = N_2 = 1.15 \cdot 10^{11}$, and a bunch spacing of 25ns (40 MHz) of the 2808 bunches leading to $\mathcal{L}^{\text{design}} \simeq 10^{34} \text{ cm}^{-2} \text{ s}^{-1} = 10 \text{ nb}^{-1} \text{ s}^{-1}$.

4.2 BEAM LUMINOSITY

- unit of cross section
 - $1\text{b} = 100\text{ fm}^2 = 10^{-24}\text{ cm}^2$. Typical values in nb-fb regime.
- unit of instantaneous luminosity $10^{34} - 10^{35}\text{ cm}^{-2}\text{s}^{-1}$
- $\sigma(\text{pp}) \approx 80\text{ mb}$

$$\frac{dN}{dt} = \mathcal{L}\sigma$$

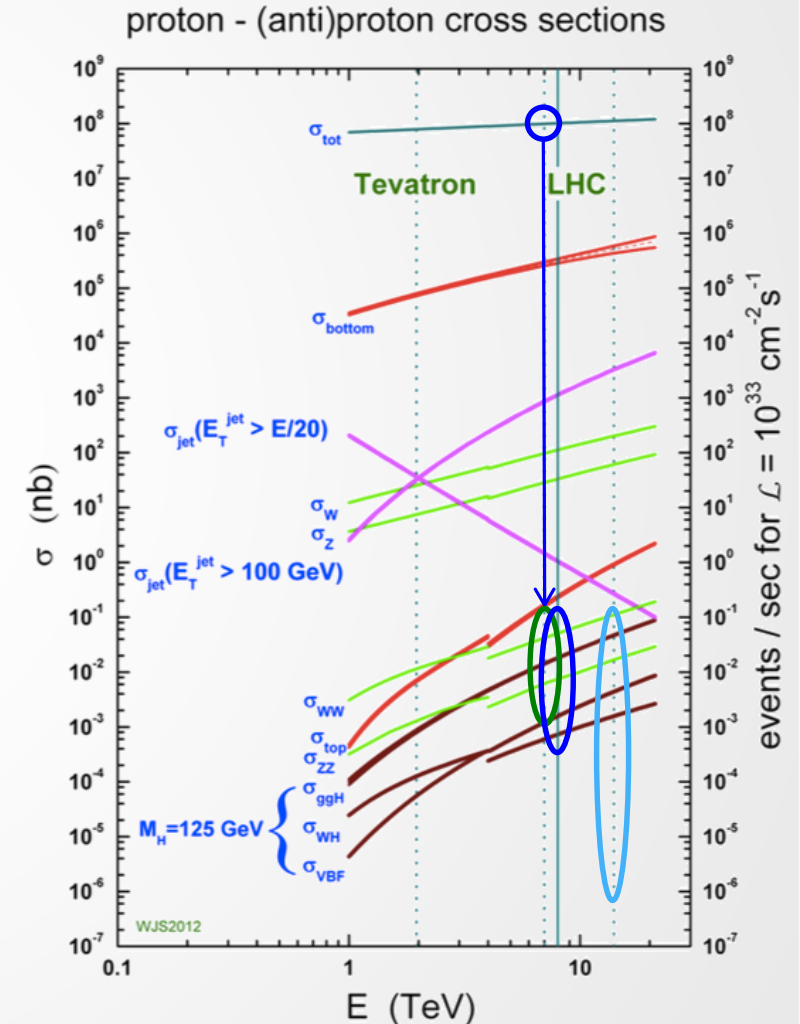
$$N = \int dt \mathcal{L}(t) \cdot \sigma \cdot \epsilon(t)$$

number of produced events
[1]

Luminosity
[nb⁻¹ s⁻¹]

efficiency
[1]

- LHC rates for 13 TeV: $\sim \mathcal{O}(1/\text{s})$ tt-pairs and $\mathcal{O}(10^2/\text{s})$ Z bosons
- LEP-I at the Z pole
 - $\sigma(e^+e^- \rightarrow Z) \cdot \text{BR}(Z \rightarrow \mu^+\mu^-) \approx 60\text{nb} \cdot 3.4\% \approx 2\text{nb}$
 - $\mathcal{L} \approx 10^{32}\text{ cm}^{-2}\text{ s}^{-1} = 0.1\text{ nb/s} \rightarrow \mathcal{O}(1/5\text{s})\text{ Z}$



4.2 BEAM LUMINOSITY

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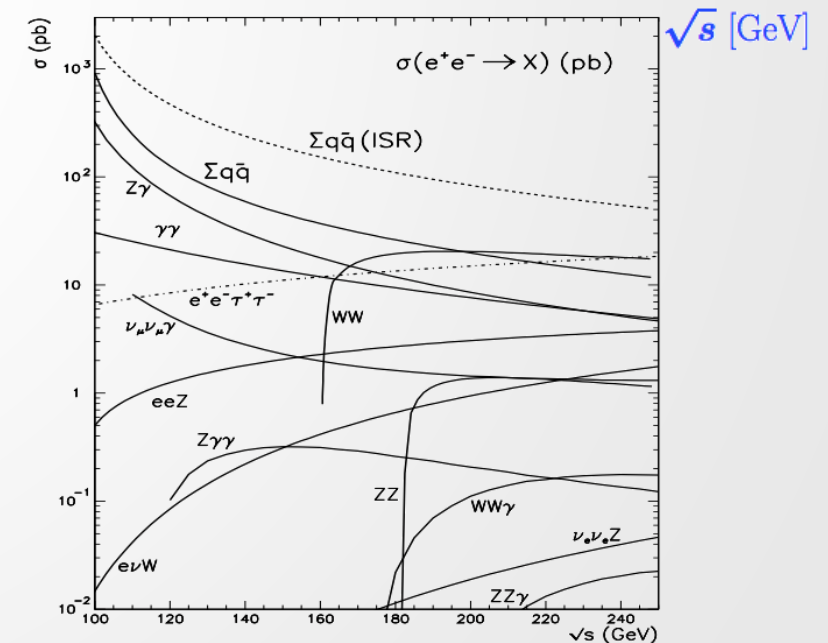
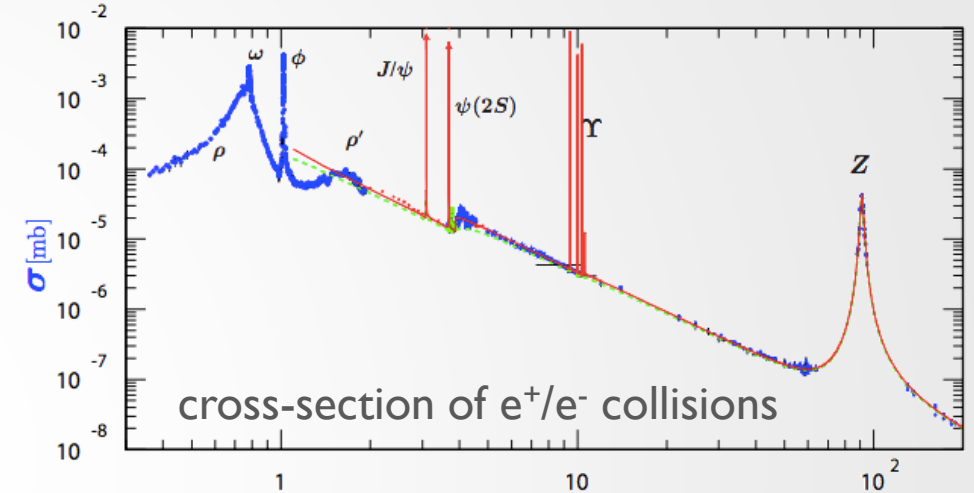
$$\frac{dN}{dt} = \mathcal{L}\sigma$$

$\frac{\text{time}}{[s]} \quad \frac{\text{cross-section}}{[nb]}$

$$N = \int dt \mathcal{L}(t) \cdot \sigma \cdot \epsilon(t)$$

number of produced events $[1]$ Luminosity $[nb^{-1}\text{ s}^{-1}]$ efficiency $[1]$

- LHC rates for 13 TeV: $\sim O(1/\text{s})$ tt-pairs and $O(10^2/\text{s})$ Z bosons
- LEP-I at the Z pole
 - $\sigma(e^+e^- \rightarrow Z) \cdot \text{BR}(Z \rightarrow \mu^+\mu^-) \approx 60\text{nb} \cdot 3.4\% \approx 2\text{nb}$
 - $L \approx 10^{32}\text{ cm}^{-2}\text{ s}^{-1} = 0.1\text{ nb/s} \rightarrow O(1/5\text{s})\text{ Z}$



4.3 EMITTANCE AND AMPLITUDE FUNCTION

- With $\pi\sigma_x\sigma_y \simeq \pi\sigma^2 = \varepsilon\beta^*$ we write the luminosity

$$\mathcal{L}^{(beams)} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} = \frac{N_1 N_2 f N_b}{4\varepsilon\beta^*}$$

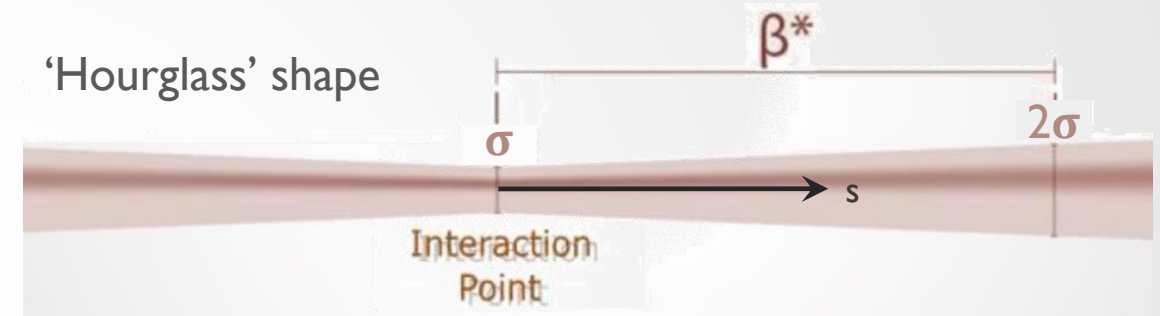
in terms of

- the transverse emittance ε [m], the smallest opening the particles fit through, and
- the amplitude function β^* which defines the distance along z at which this opening doubles:

$$\pi\sigma^2(s) = \varepsilon\beta(s)$$

$$\beta(s) = \beta^* \left(1 + \left(\frac{s}{\beta^*} \right)^2 \right)$$

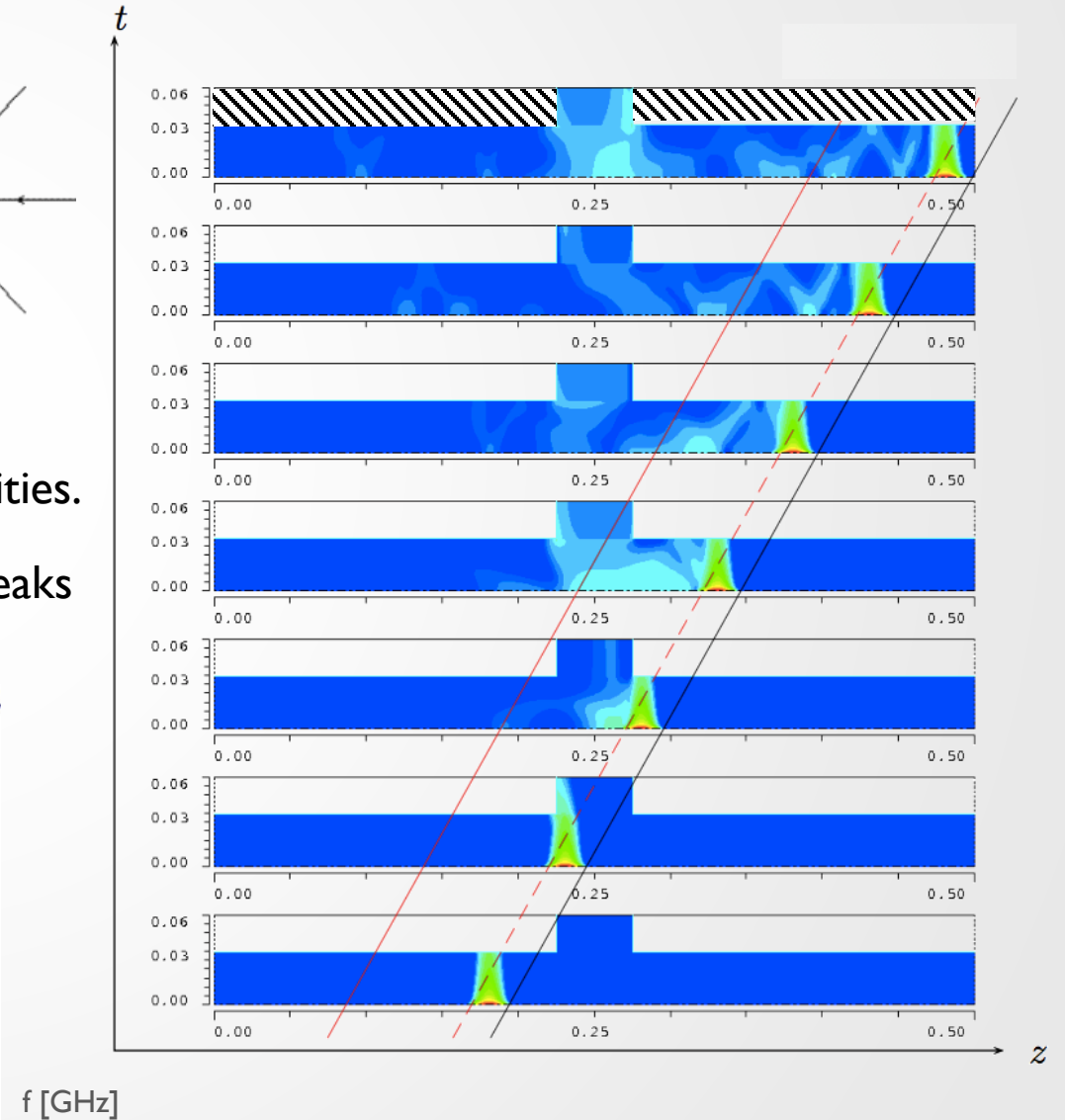
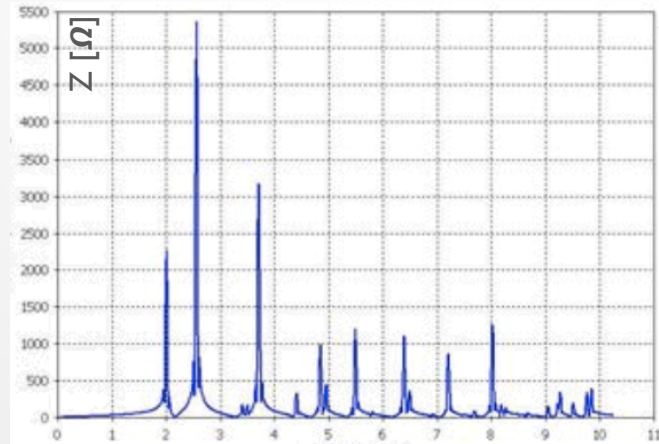
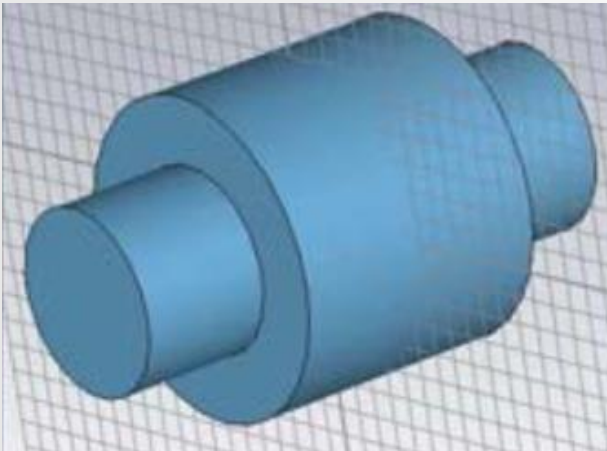
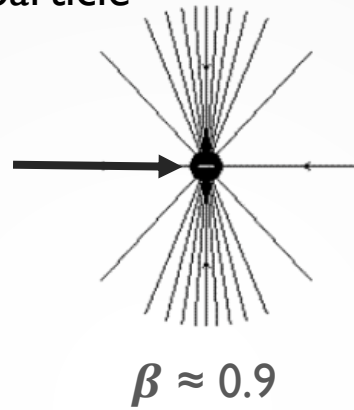
- ε is determined by the quality of the bunch preparation in the injector chain
 - can not be changed by focusing (Liouville theorem)
 - low emittance is desired



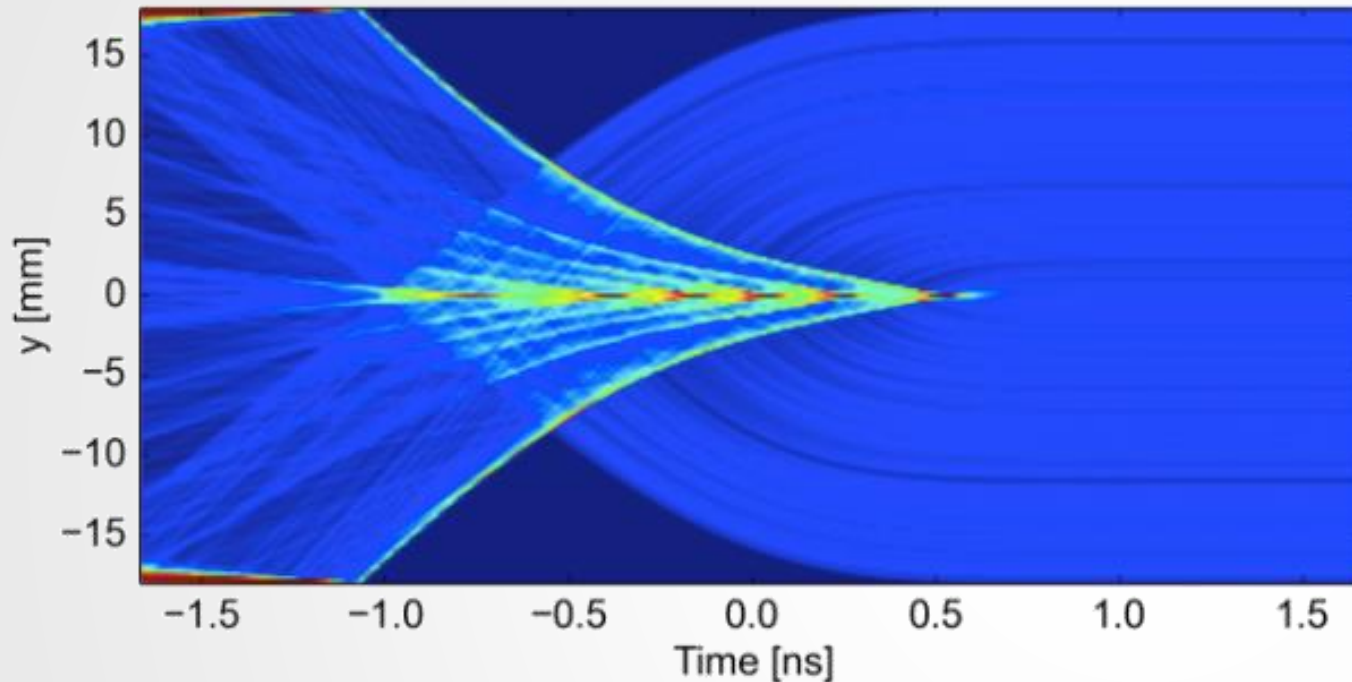
- Sources for emittance blow-up
 - injection/transfer mismatch
 - scattering on beam gas
 - beam resonances, intra-bunch collective instabilities
 - Intra-beam scattering
- β^* (unit length) is determined by the beam optics.
 - A low value of β^* means fast blow-up with z .
 - Typical values at the LHC are 15-50 cm

4.4 WAKE FIELDS AND IMPEDANCES

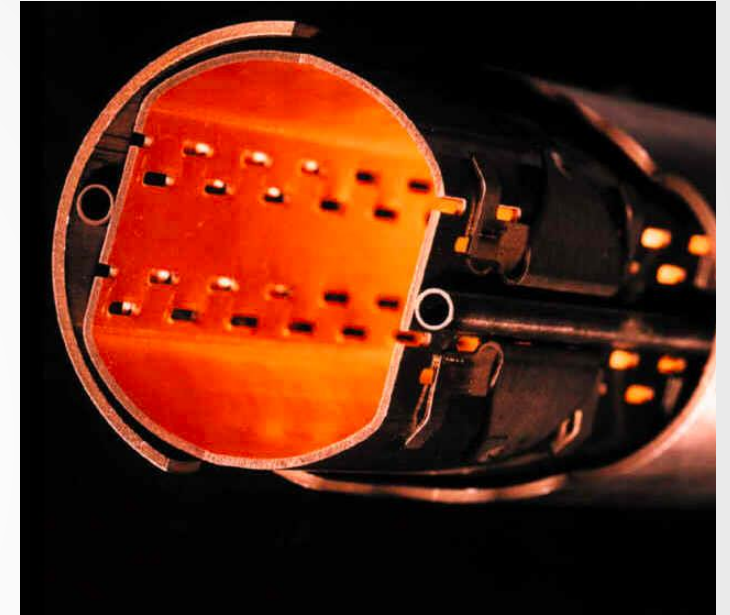
- The electric field of an ultra-relativistic charged particle has a longitudinal extension proportional to γ^{-1} .
- The interaction with the beam pipe surface, in particular at cavities, collimators and tapering structures in the vicinity of the interaction regions, creates wake fields.
- Wake fields interact with the beam and cause collective instabilities.
- Cavities are analyzed in the frequency domain, where narrow peaks in the impedance correspond to resonances



4.5 ELECTRON CLOUDS AND SCRUBBING



simulation of electron cloud of a bunched proton beam

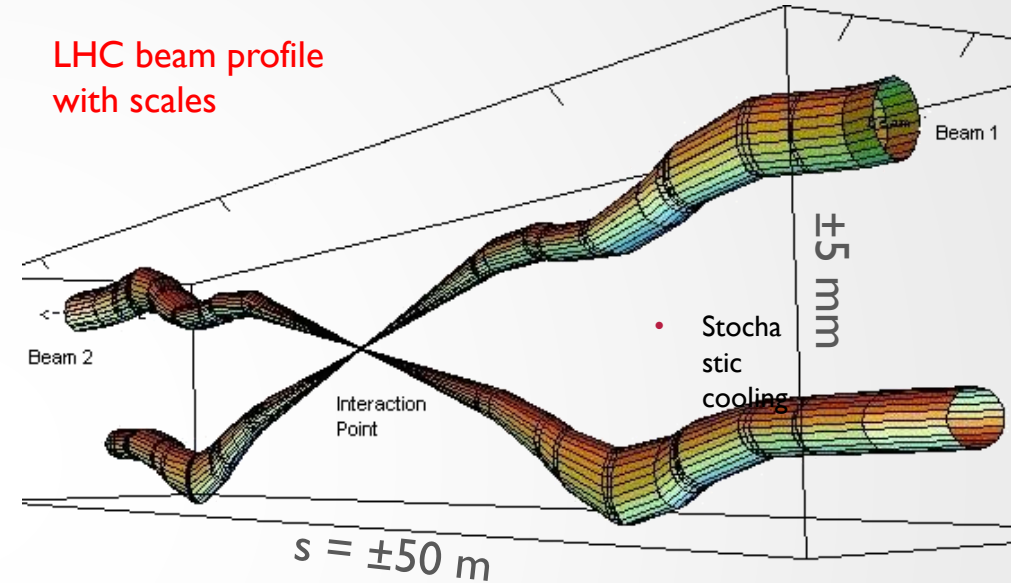
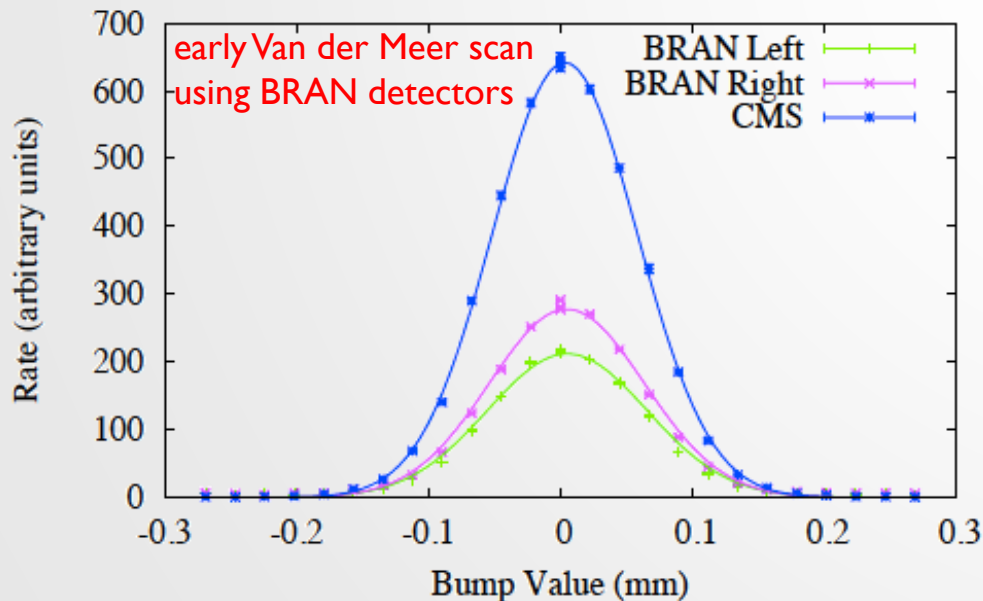


beam screen in LHC dipole magnets

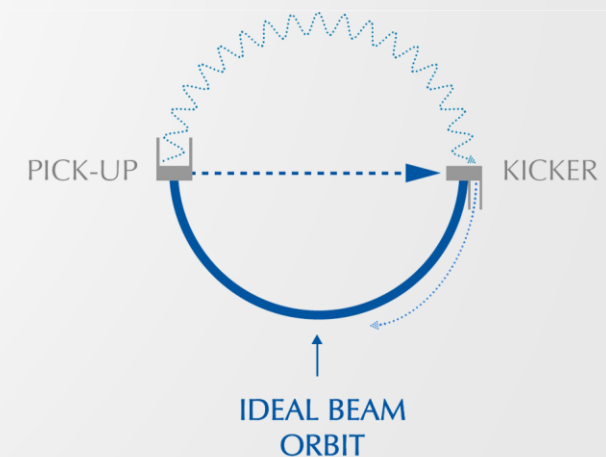
- The beam can release electrons which then resonantly interact with the beam (oscillating e^- clouds), and subsequently cause the release of more debris compromising the vacuum.
- The beam screen shields the magnet from interaction with the beam. Its surface, however, can hold residual gas (or even dust) particles that can lead to very large losses ('UFO') when released.
- In order to mitigate the effect, short 'scrubbing' runs with very high intensity but low energy clean the beam pipe.

4.6 VAN DER MEER SCANS AND STOCHASTIC COOLING

- Measure beam profile by displacing the beams transversally and observing the change in event rate ('Van der Meer scans')
 - provides absolute luminosity at hadron machines
 - co-moving beam displacement used for calibrating of the $\Delta_{x,y}$ measurement
 - invented at ISR (CERN), used at RICH, LHC

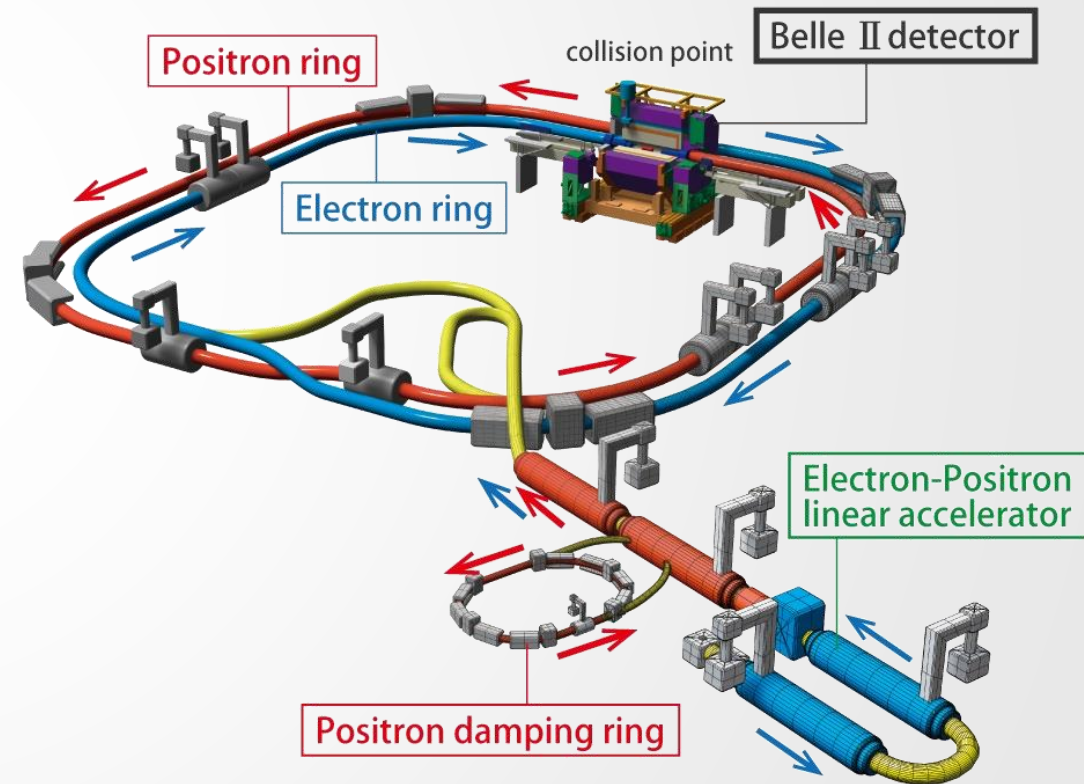
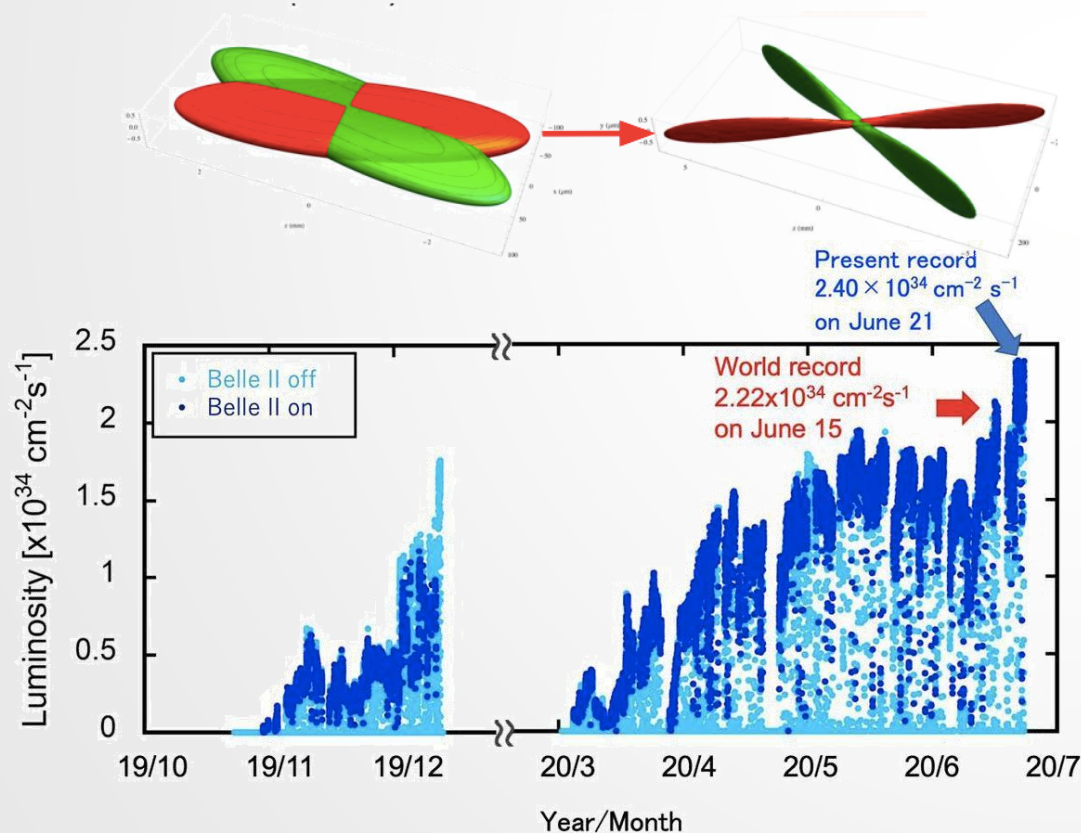


- Stabilize beams: Stochastic cooling
 - pick up RF signal
 - send signal *through* the ring
 - kicker magnet corrects the orbits individually (stochastic)
 - invented by Simon Van der Meer

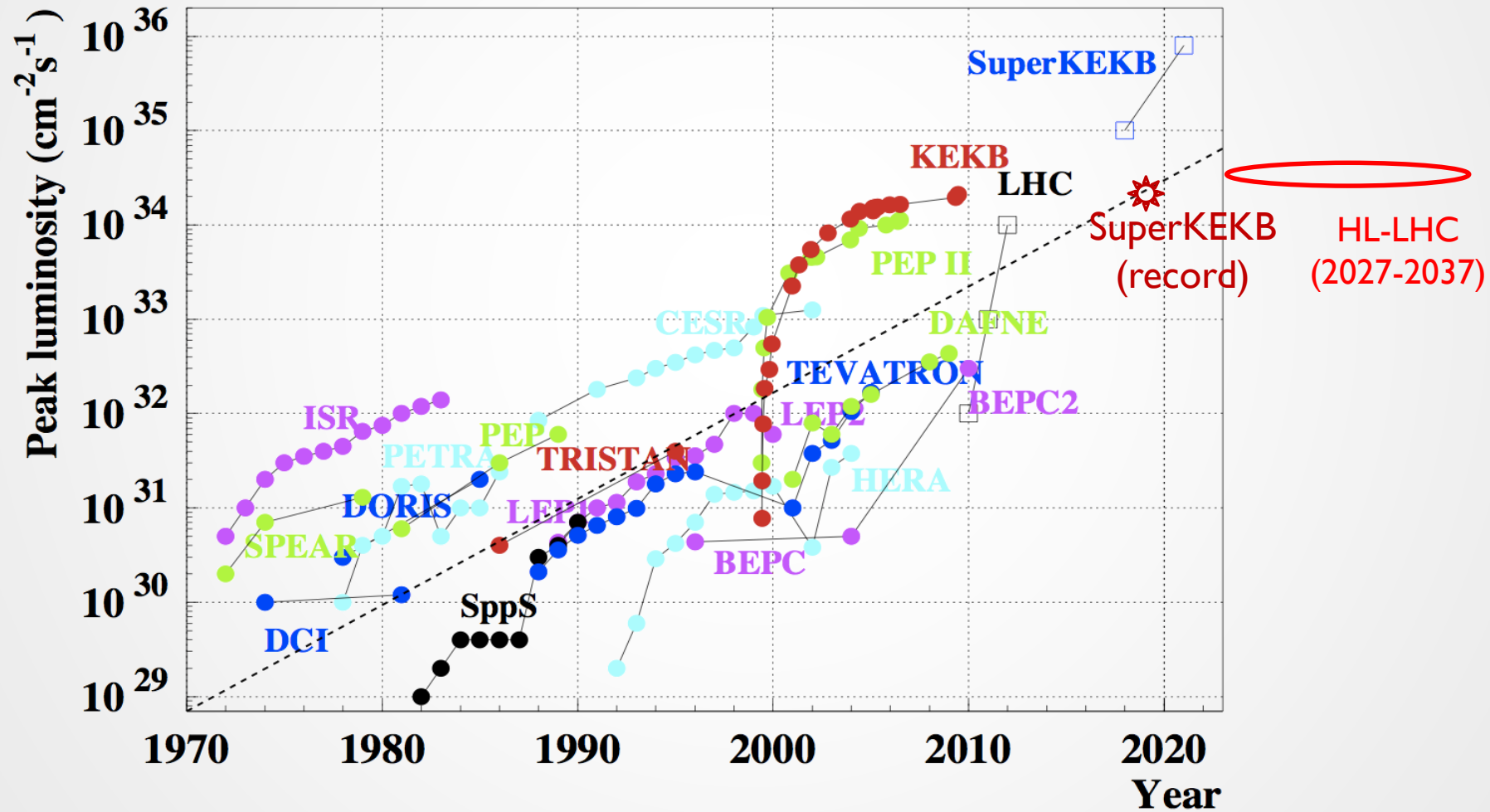


4.7 LUMINOSITY RECORD (SUPERKEKB)

- Collisions of 7 GeV e^- on 4 GeV e^+ producing $\Upsilon(4S)$ decaying to $B\bar{B}$
 - Luminosity: $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ to $8 \cdot 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
 - Current world-wide luminosity record on June 21st, 2020
 - 220nm \rightarrow 50nm beam width using 'nano beam scheme'



4.8 COLLIDERS AT THE LUMINOSITY FRONTIER



5. PRESENT FACILITIES & FUTURE CONCEPTS

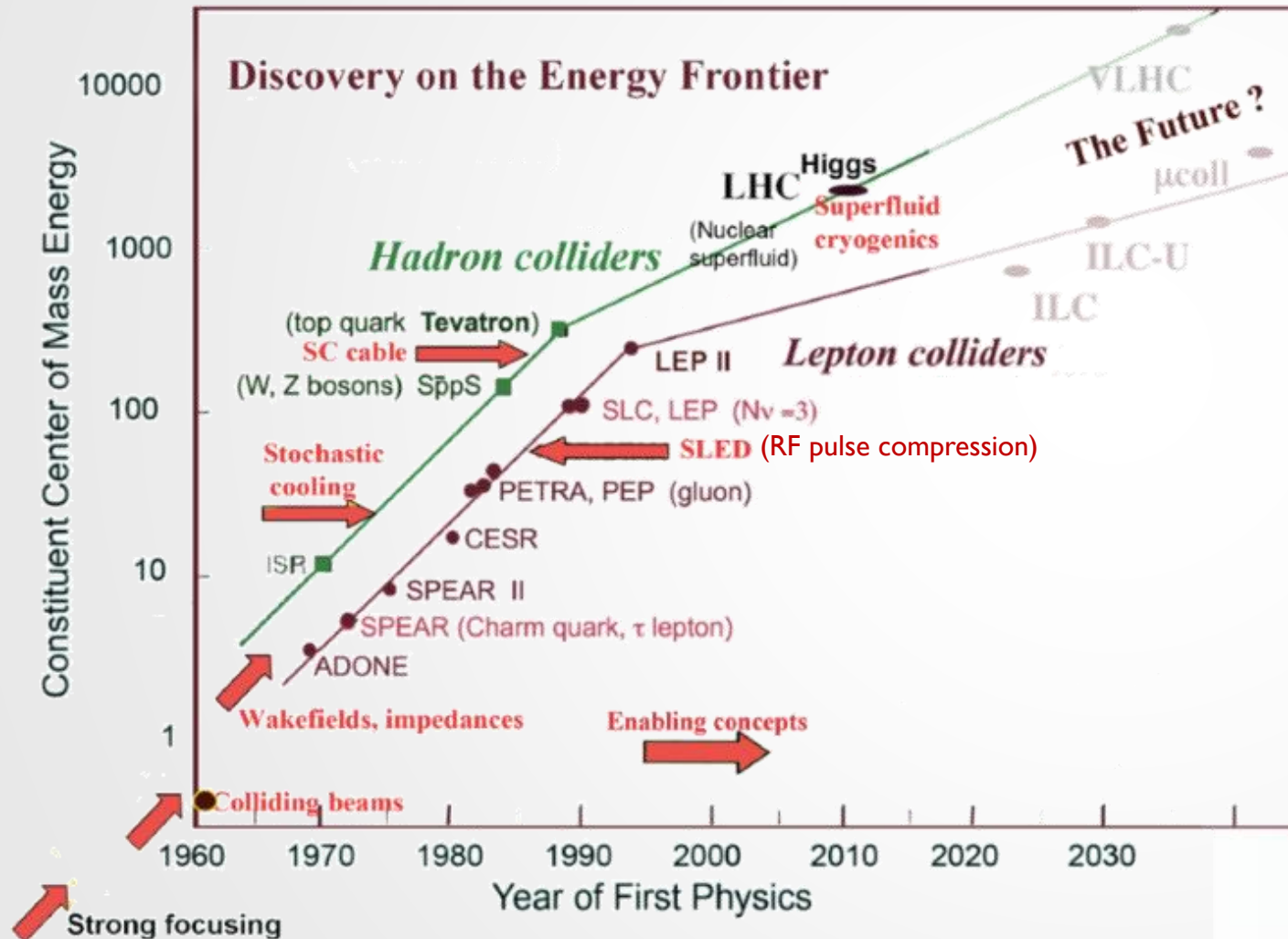
5.1 PRESENT FACILITIES

<http://pdg.lbl.gov/2016/reviews/rpp2016-rev-hep-collider-params.pdf>

collider	facility	operation	time	\sqrt{s} (GeV)	length	E_{beam} (GeV)	Luminosity $\text{cm}^{-2} \text{s}^{-1}$	main experiments
SLC	SLAC	e^+e^-	'87-'98		2x1.45 km	50	$2.5 \cdot 10^{30}$	MarkII, SLD
PEP-II			'99-'08		2.2 km	$e^- : 9, e^+ : 3$	$1.2 \cdot 10^{33}$	Babar
Hera	DESY	ep	'92-'07	300	6.3 km	$e^- : 30, p : 920$	$7.5 \cdot 10^{31}$	ZEUS, H1, Hera-b, Hermes
LEP	CERN	e^+e^-	'89-'00	89-209	27 km	45.6-104.5	10^{32}	Aleph, Delphi, L3, Opal
VEPP-4M	Budker Novosibirsk	e^+e^-	'94-		366 m	6	$2 \cdot 10^{31}$	KEDR, ROKK-I
VEPP-2000			'10-		24 m	1	10^{32}	SND, CMD-3
BEPC-II	China	e^+e^-	'08-		240 m	1.89-2.3	$8.53 \cdot 10^{32}$	BES-III
DAΦNE	Frascati	e^+e^-	'99-		98 m	0.5	$4.53 \cdot 10^{32}$	KLOE-2
RHIC	BNL	Au-Au, Cu-Cu, d-Au	'00-		3.9 km	255	$1.2 \cdot 10^{32}$ (AuAu)	STAR, PHENIX, PHOBOS, BRAHMS
SppS(SpS)	CERN	p/pbar (pp)	'81-'91	400	6.9 km	315(450)	$8 \cdot 10^{30}$	UA1, UA2
Tevatron	FNAL	p/pbar	'87-'08	1.96 TeV	6.28 km	980	$4.31 \cdot 10^{32}$	CDF, D0
LHC	CERN	pp / HI	'09 -	13 / 14 TeV	27 km	6500/7000	$2 \cdot 10^{34}$	ATLAS, CMS, LHCb, Alice
KEK-B	KEK	e^+e^-	'99-'10		3.0 km	$e^- : 8, e^+ : 3.5$	$2.1 \cdot 10^{34}$	Belle
SuperKEKB	KEK	e^+e^-	'16 -		3.0 km	$e^- : 7, e^+ : 4$	$8 \cdot 10^{35}$	Belle-II

5.2 LIVINGSTON DIAGRAM

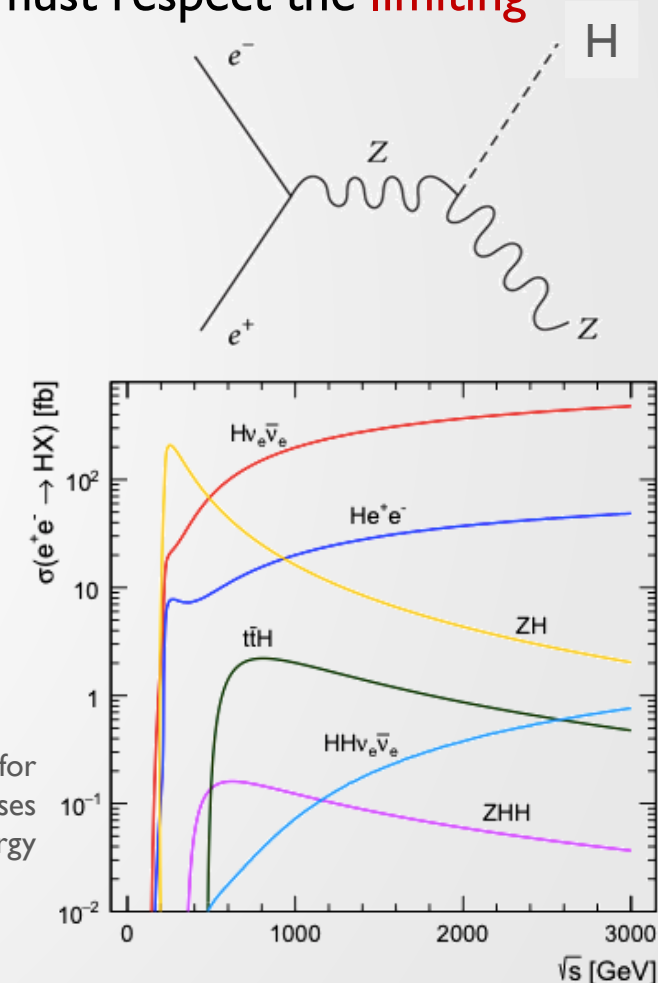
Snowmass report '13, Chapter 6



- Almost exponential growth of achievable energy with time
- Usage of superconductors mark import milestones
 - Cables, magnets, cooling
- Present and near-future facilities
 - LHC/HL-LHC for pp
 - SuperKEKB for e^+e^-
- The e^+/e^- energy frontier is the next logical goal.
- Requires long term planning!

5.3 EUROPEAN STRATEGY FOR PARTICLE PHYSICS

- The CERN Council set up the European Strategy group (ESG) to define the future strategy for particle physics in Europe. **Technological challenges** meet the **big physics questions** and must respect the **limiting factors of colliders**.
- Important areas of future research in particle physics
 1. Higgs boson precision physics
 - Why not just collide e^+e^- to produce a Higgs boson? Too weakly coupled!
 - Need for “Higgsstrahlung”: $E(e^+e^-) > 240$ GeV for Higgs in ZH production
 - Little is known about the Higgs potential!
 2. Electroweak physics, precision tests of the Standard Model
 3. Strong interactions, precision QCD, hot and dense media
 4. Flavor physics of light and heavy mesons
 5. Beyond the standard model & dark matter searches, anomalous interactions



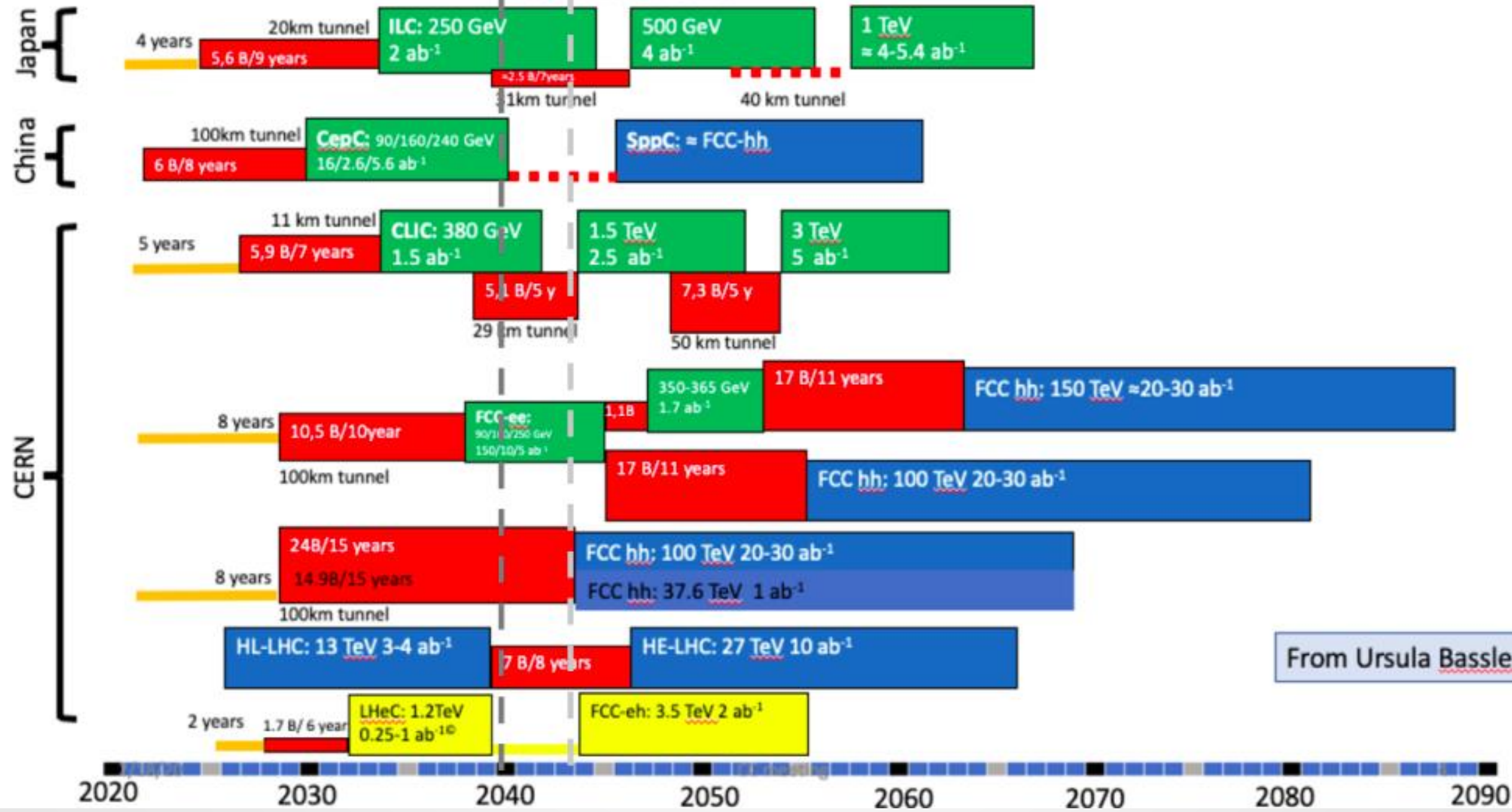
5.3 EUROPEAN STRATEGY FOR PARTICLE PHYSICS

- Remember the **main limitations!**
 - Circular e^+e^- colliders are limited by **synchrotron radiation**. No problem for linear colliders or circular hh colliders.
 - Circular hh colliders are limited by the strength of the magnets.
 - Linear e^+e^- colliders are (mostly) limited in the achievable integrated luminosity
- Future **Circular** Collider projects
 - CERN/FCC: FCC-ee and FCC-hh
 - design studies for proton-proton operation (FCC-hh), e^+e^- operation (FCC-ee) and eh operation
 - 100 km tunnel $\approx 3.6 \times R(\text{LHC})$
 - magnets based on Nb_3Sn instead of NbTi with $16.3\text{T} \approx 2 \times B(\text{LHC}) \rightarrow E(\text{FCC}) \approx 7.2 E(\text{LHC}) = 100\text{ TeV}$ for FCC-pp
 - CEPC/SPPC (China): 100km collider with 12T (later 24T) magnets; e^+e^- and pp operation
- Future **Linear** Colliders for e^+e^-
 - CLIC $L=50\text{km}$, $\sqrt{s} = 190\text{-}3000\text{ GeV}$. Two beam-scheme, extracting energy from a high-intensity low-energy beam
 - ILC 250 GeV – 1 TeV in Japan

Possible scenarios of future colliders

■ Proton collider
■ Electron collider
■ Electron-Proton collider

— Construction/Transformation: heights of box construction cost/year
— Preparation



5.3 EUROPEAN STRATEGY FOR PARTICLE PHYSICS

- Current status is summarized in the [2020 update](#); a result of ≈ 15 years of discussion
- Near term: exploit the full physics potential of the high-luminosity LHC (2026-2036): **HL-LHC**

High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*

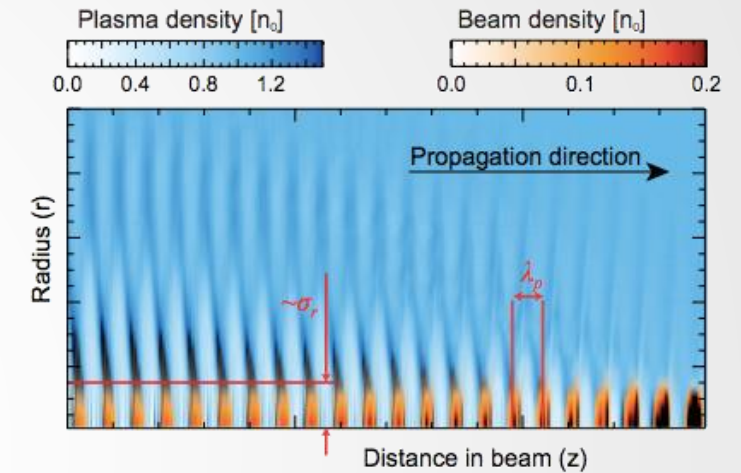
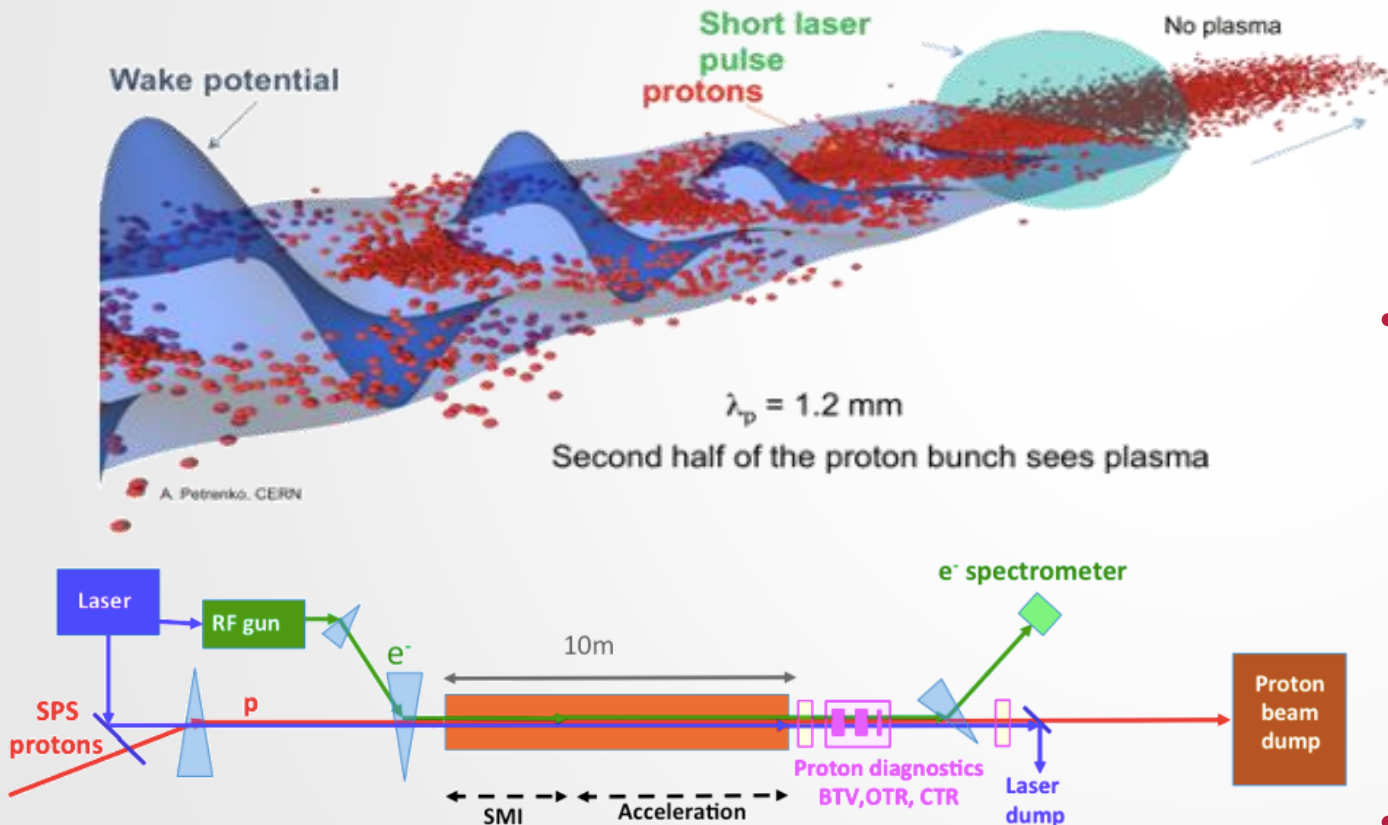
• Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

- Start R&D for 100TeV magnets & *investigate technical and financial feasibility* of a 100 TeV collider

5.4* R&D: AWAKE - WAKEFIELD ACCELERATION

- Future electron linear colliders benefit from accelerating gradients
- For 1 TeV electrons, need e.g. 10-100GV/m for tens of meters



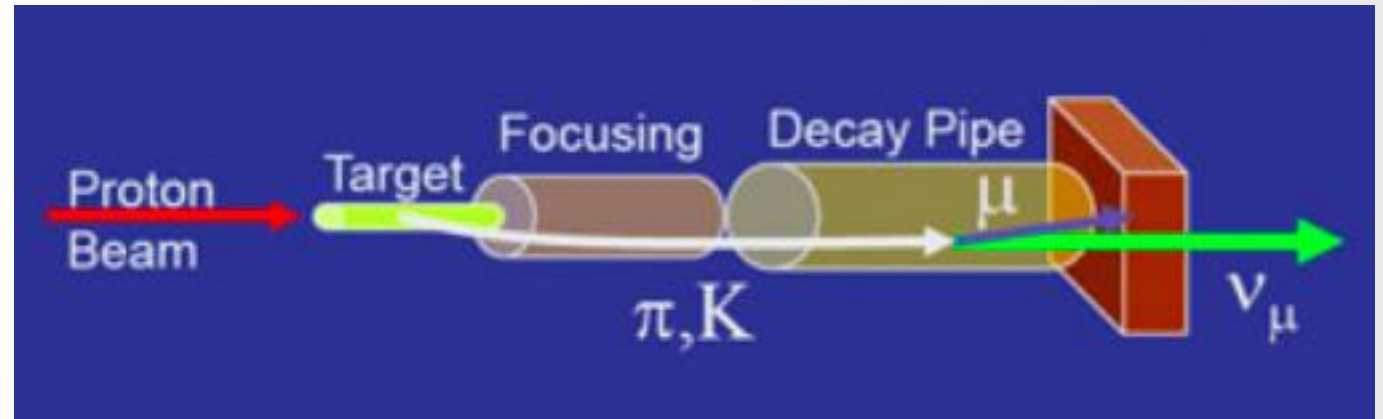
- Awake - Advanced WAKEfield Experiment
 1. creates a Rb plasma by a 4 TW 120fs laser pulse
 2. followed by a bunched proton beam
 3. self-modulating instability of the proton beam in plasma creates a wake potential
 4. electrons are accelerated in the wake field
- achieved acceleration to 2 GeV in June '18

THE END!

NEUTRINO BEAMS

Detection of the Free Neutrino, Phys. Rev. 92, 830 (1956)
History of accelerator neutrino beams, Dore et.al. (2018)

- It took 26 years from Pauli's 1930 “desperate remedy” to restore energy conservation in β decay until in 1953 the free neutrino was discovered by using intense Hanford reactor flux on a p target $\nu + p \rightarrow \beta^+ + n$.
- Already in 1962 the first neutrino beam at AGS (Alternating Gradient Synchrotron, BNL) from decays of targeted pions (mostly ν_μ) confirmed that ν_e and ν_μ are different.
- Pions and Kaons are produced in collisions of protons on a fixed target.
- A main challenge is to focus the charged pions using ‘magnetic horns’.
- The mesons decay mostly to ν_μ and $\bar{\nu}_\mu$.
- The polarity can be selected, producing beams primarily consisting of ν_μ and $\bar{\nu}_\mu$.
- In rarer cases, beam dump experiments at proton synchrotrons exploit neutrino beams that are nearly equally mixed in neutrino flavor.
- Famous neutrino beam lines: NuMI, Booster@FNAL (Minerva, Microboone), J-PARC (Japan, T2K exp.)



COCKROFT-WALTON VOLTAGE MULTIPLICATION

