Colliders of Tomorrow

Accelerator Fundamentals: Part II

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U.S. DEPARTMENT OF ENERGY
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SLAC NATIONAL ACCELERATOR LABORATORY

Acknowledgements & References

- Eric Prebys & Vladimir Shiltsev CMS Data School Talks from 2022/2020
- Michael Fazio
- US Particle Accelerator School
  - https://uspas.fnal.gov/index.shtml
  - https://people.nscl.msu.edu/~lund/uspas/ap_2021/
  - https://sites.google.com/view/uspas-2020-winter-fundamentals/course-syllabus
- Alesini, David. "Linear Accelerator Technology." *CERN Yellow Reports: School Proceedings* 1 (2018): 79-79.
- Kain arXiv:1608.02449v1 Beam Dynamics and Beam Losses – Circular Machines
- Many more references on slides and in speaker notes

Outline

Part I

- Examples and Uses of Accelerator Facilities
- Colliders of Tomorrow
- Major Systems and Components of Accelerator Facilities

Part II

- Basic Accelerator Physics
- Future Directions

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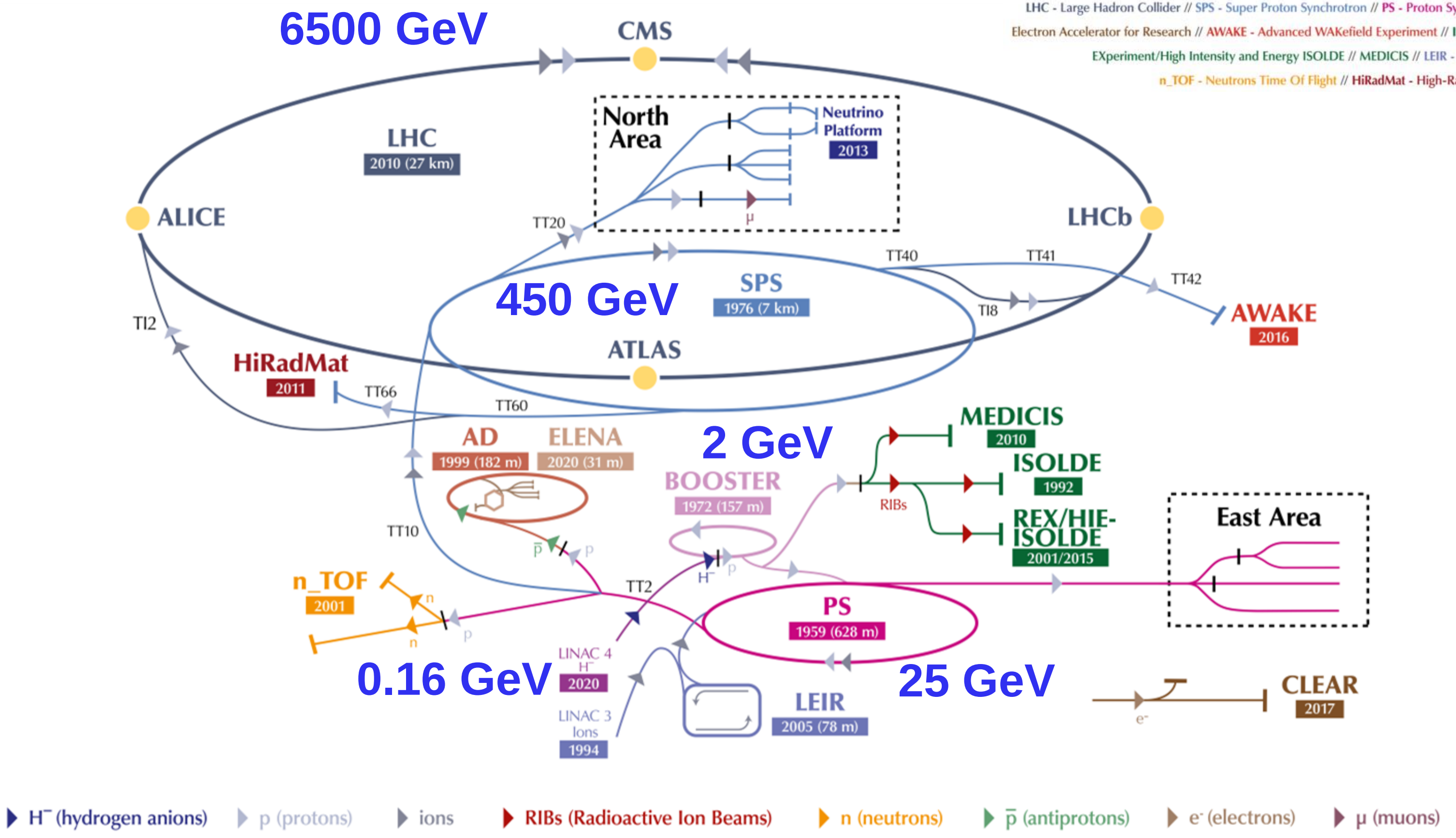
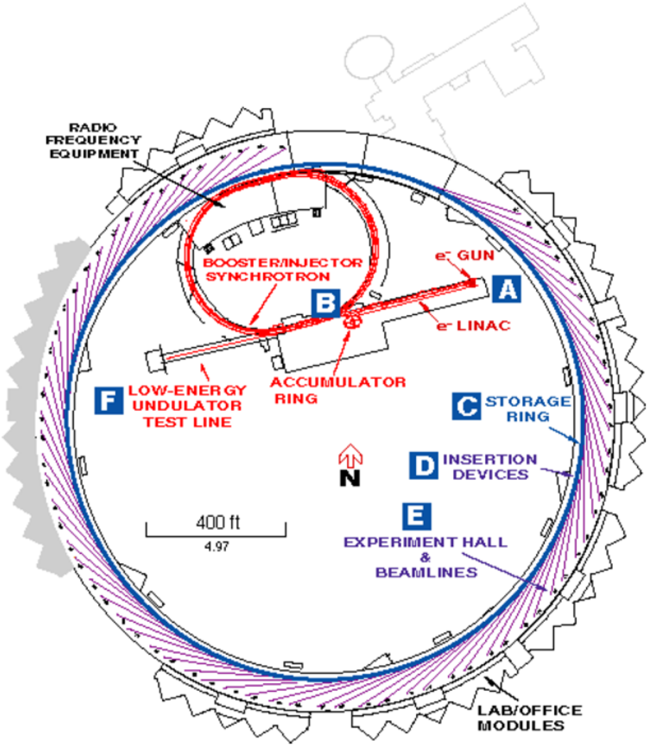
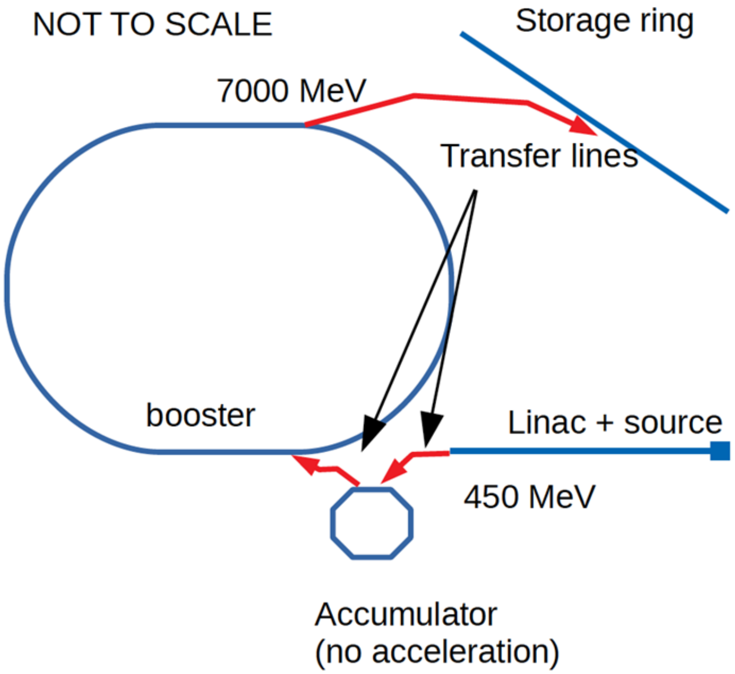
CERN Accelerator Complex



LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

Schematic View of the Advanced Photon Source





NOT TO SCALE

Storage ring

7000 MeV

Transfer lines

booster

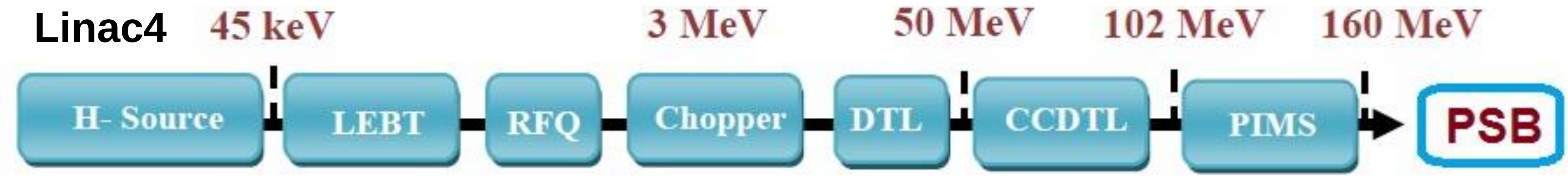
Linac + source

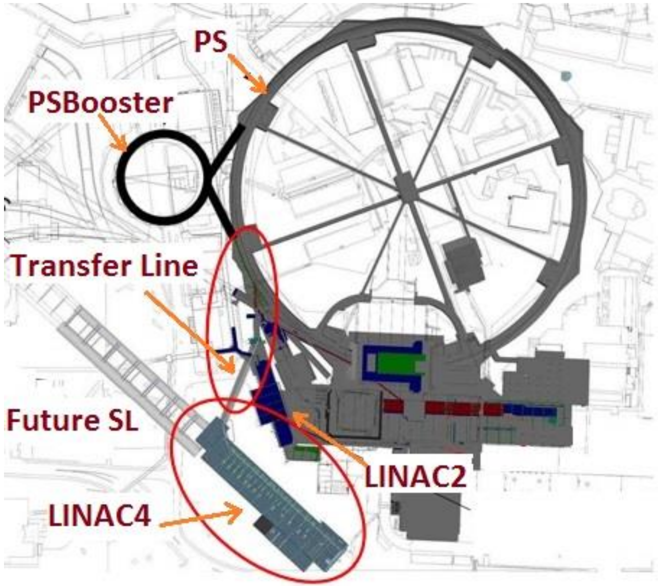
450 MeV

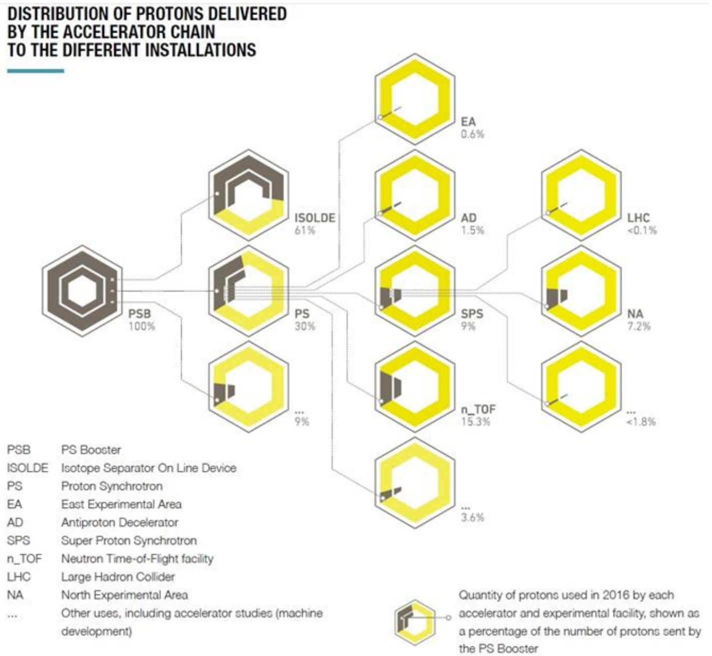
Accumulator
(no acceleration)

RF Linear Accelerator Increases Beam Energy @ CERN

Linac4







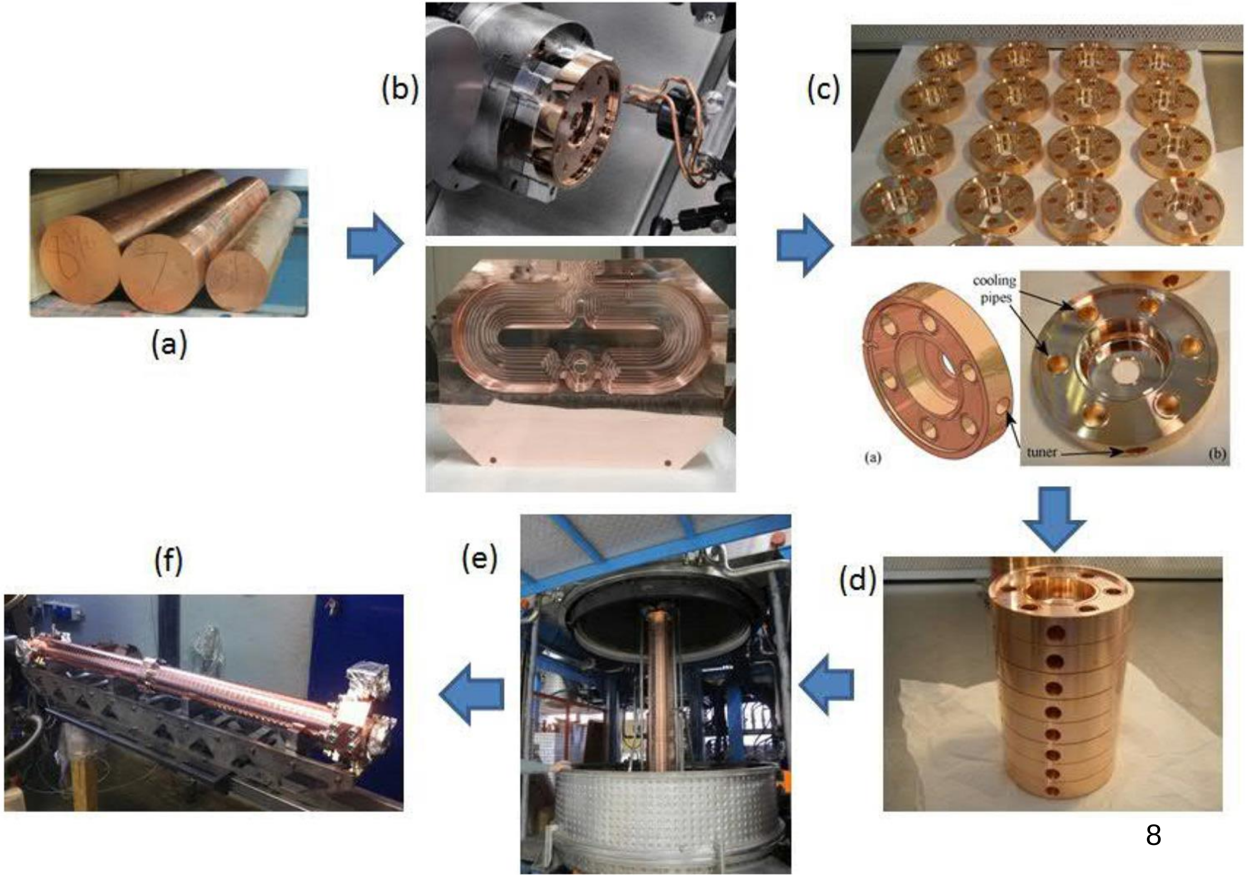
DISTRIBUTION OF PROTONS DELIVERED
BY THE ACCELERATOR CHAIN
TO THE DIFFERENT INSTALLATIONS

PSB	PS Booster
ISOLDE	Isotope Separator On Line Device
PS	Proton Synchrotron
EA	East Experimental Area
AD	Antiproton Decelerator
SPS	Super Proton Synchrotron
n_TOF	Neutron Time-of-Flight facility
LHC	Large Hadron Collider
NA	North Experimental Area
...	Other uses, including accelerator studies (machine development)

Quantity of protons used in 2016 by each accelerator and experimental facility, shown as a percentage of the number of protons sent by the PS Booster

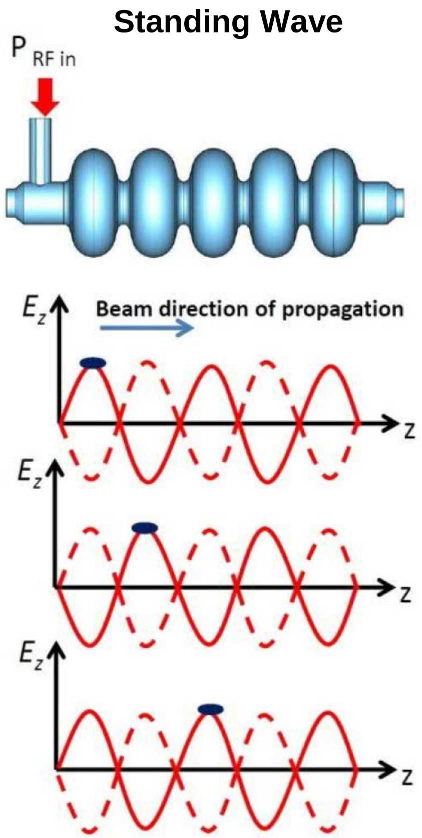
Fabrication of RF Accelerators

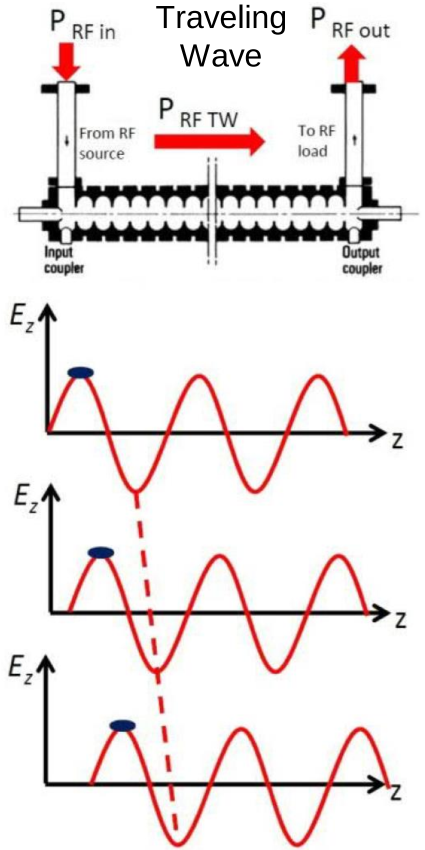
(a) OFHC forged copper; (b) realization of cells by lathes; (c) single cells machined and ready to be stacked; (d) cells piled up before brazing; (e) the structure in a vacuum or hydrogen furnace; (f) the brazed structure.



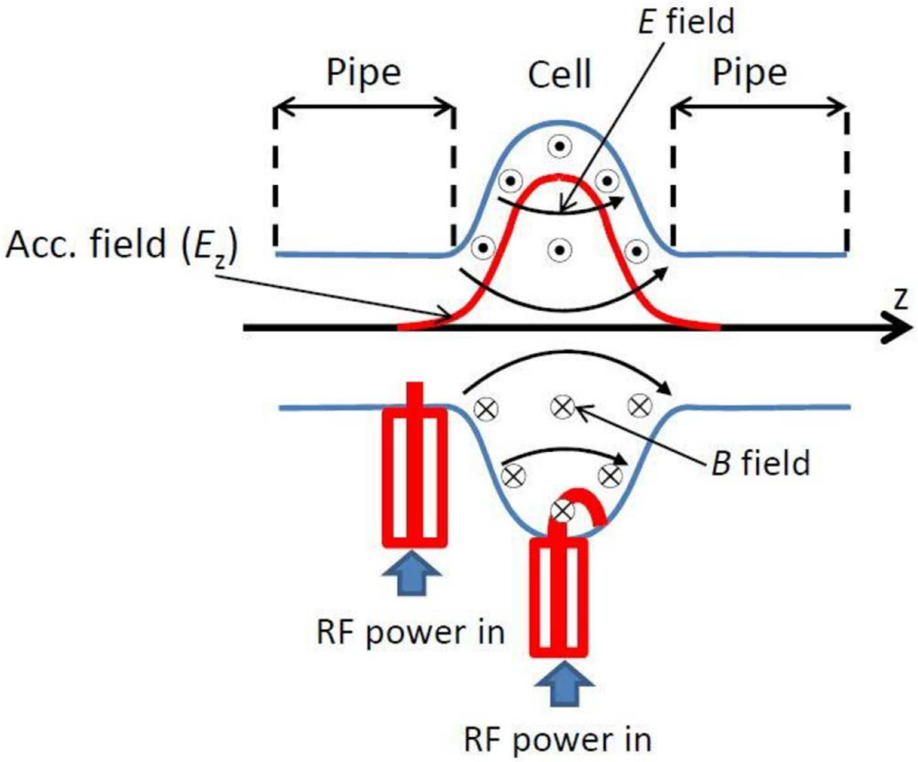
Electromagnetic Fields Used to Accelerate Particles

- Phase of electromagnetic wave needs to be controlled to match the particles velocity
- Standing Wave - fields in cavity alternate polarity in cavities and oscillate
- Traveling Wave – fields propagate with a phase velocity that matches particle velocity





Axial Electric Field Increases Kinetic Energy

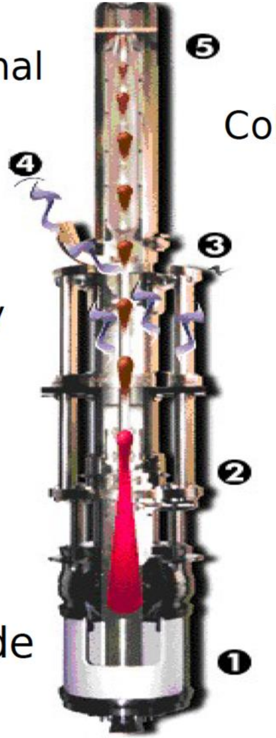


$$E_{\mathrm{z}}(z,t) = E_{\mathrm{RF}}(z)\cos\left(\underbrace{2\pi f_{\mathrm{RF}}}_{\omega_{\mathrm{RF}}} t + \varphi\right) = \mathrm{Real}\left[\tilde{E}_{\mathrm{z}}(z)e^{j\omega_{\mathrm{RF}}t}\right]$$

$$V_{\mathrm{acc}} = \left|\int_{\mathrm{cavity}} \tilde{E}_{\mathrm{z}}(z)\, e^{j\omega_{\mathrm{RF}}\frac{z}{v}} dz\right|$$

RF Sources Power the Accelerator

RF Source (Klystron)



Output large 3 GHz signal

Collector

Output cavity

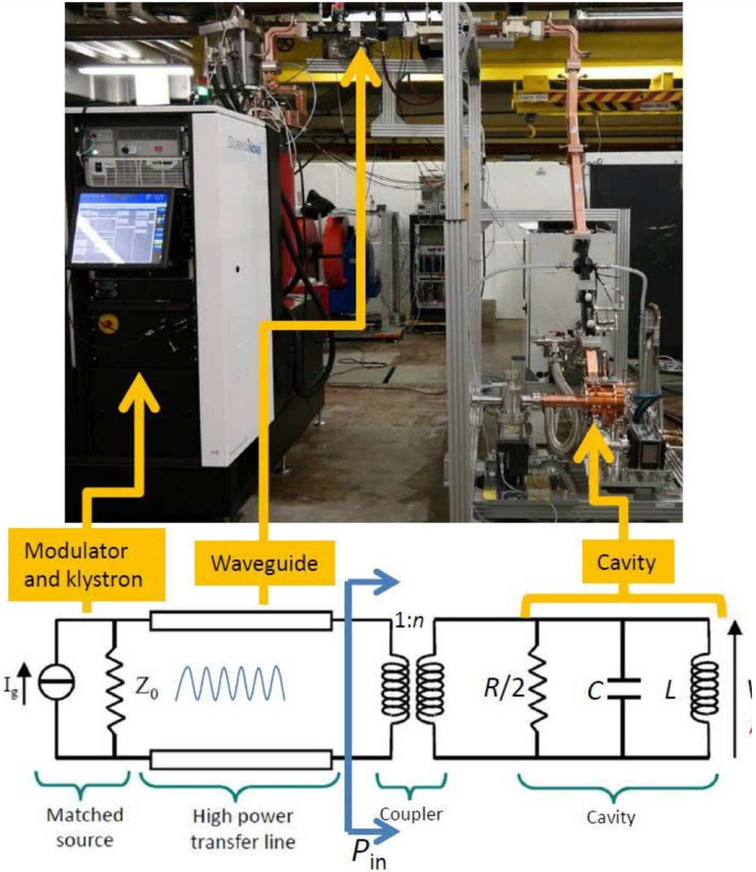
Anode

Cathode

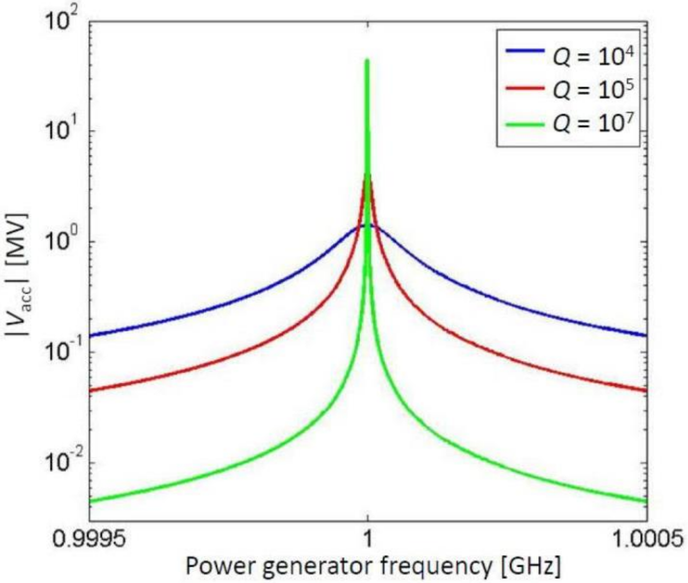
Input small 3 GHz signal

400 MHz, 500 kW LHC Klystron

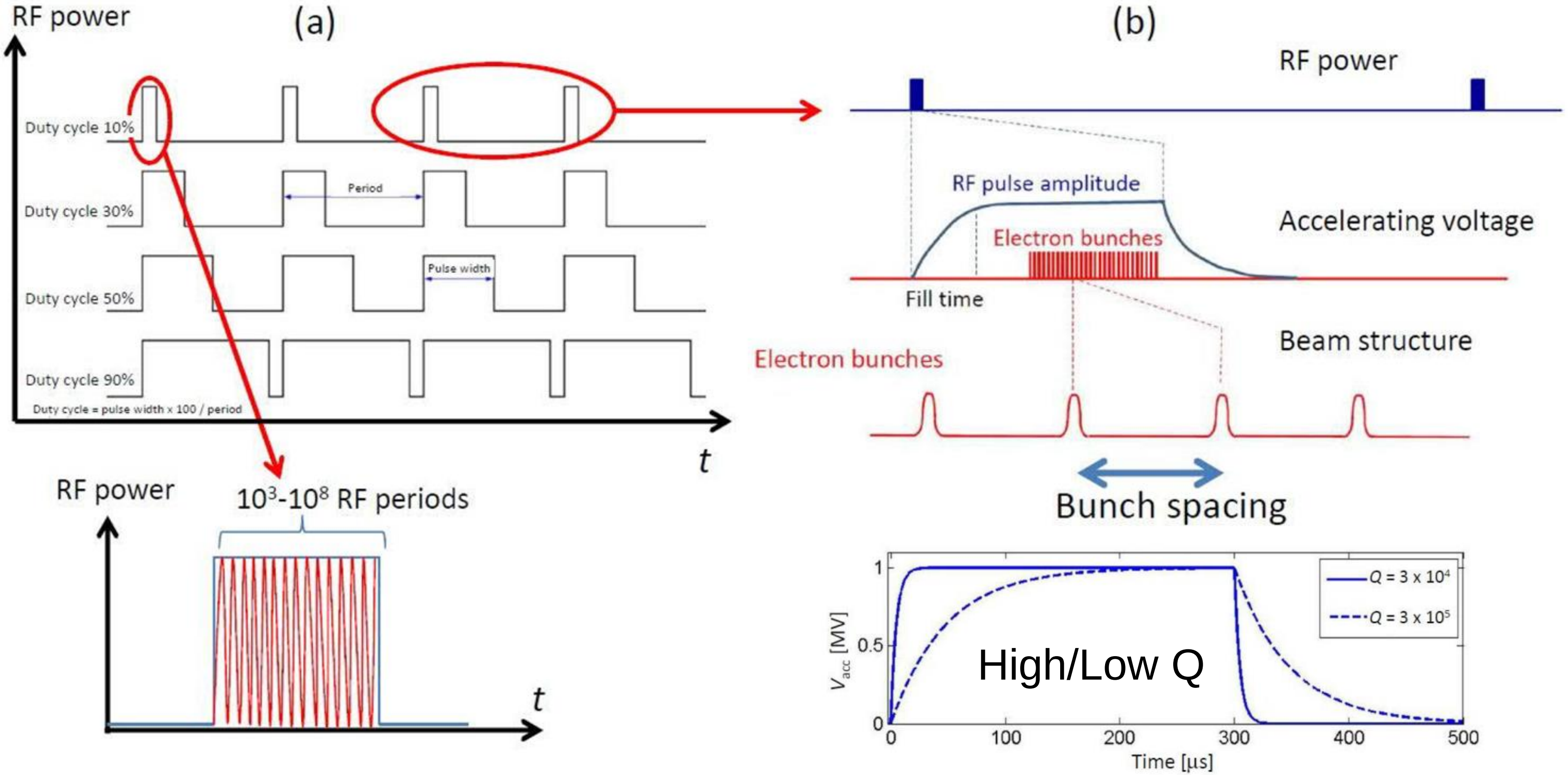
Circuit Model for Powering Accelerators



- High quality factor increases energy gain for fixed power



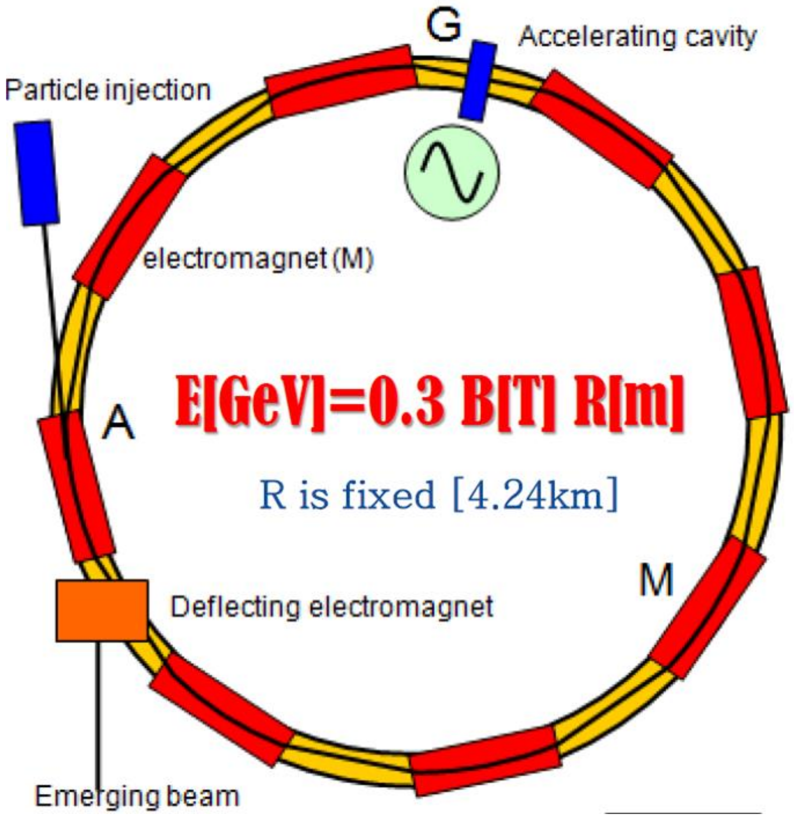
RF and Beam Pulse Structure



High/Low Q

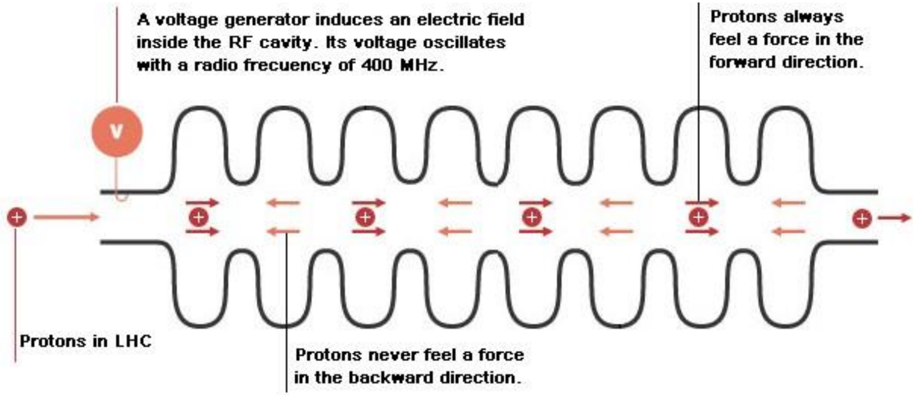
LHC Synchrotron

- Synchrotron recirculates a beam providing additional energy with each pass
- The magnetic field is increased with increasing beam energy



LHC Cryomodule

The LHC uses eight cavities per beam, each delivering 2 MV (an accelerating field of 5 MV/m) at 400 MHz. The cavities operate at 4.5 K — the LHC magnets use superfluid helium at 1.9 K.

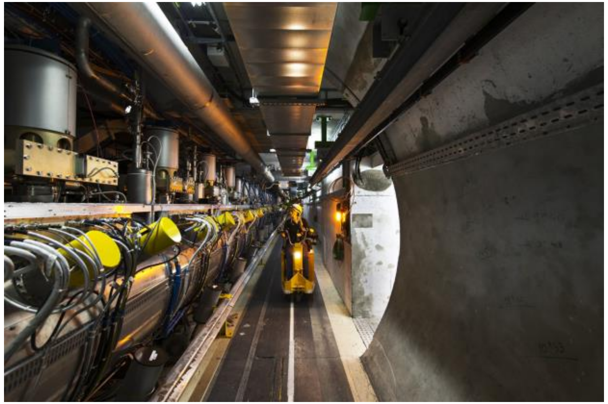


A voltage generator induces an electric field inside the RF cavity. Its voltage oscillates with a radio frecuency of 400 MHz.

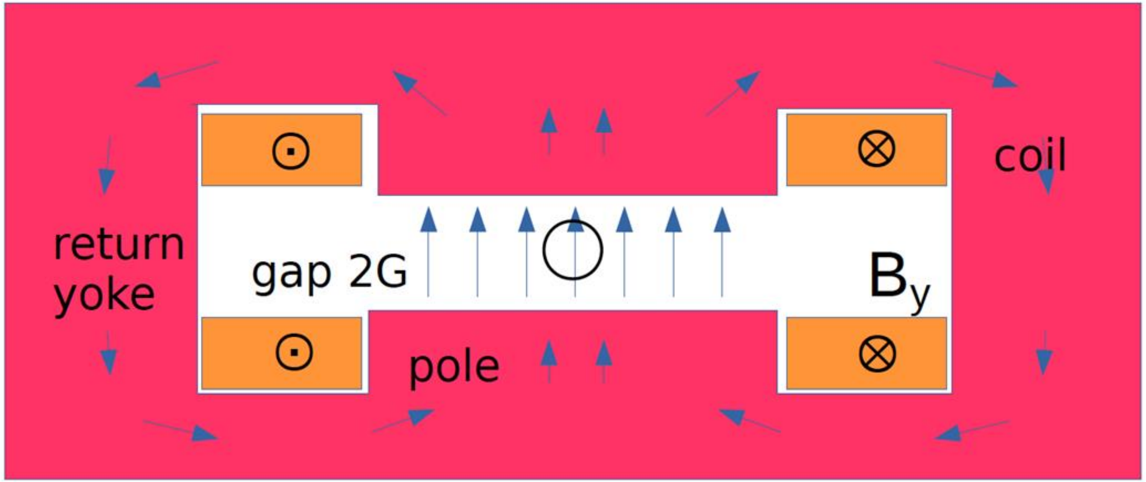
Protons always feel a force in the forward direction.

Protons in LHC

Protons never feel a force in the backward direction.



Magnets Guide and Transport the Beam

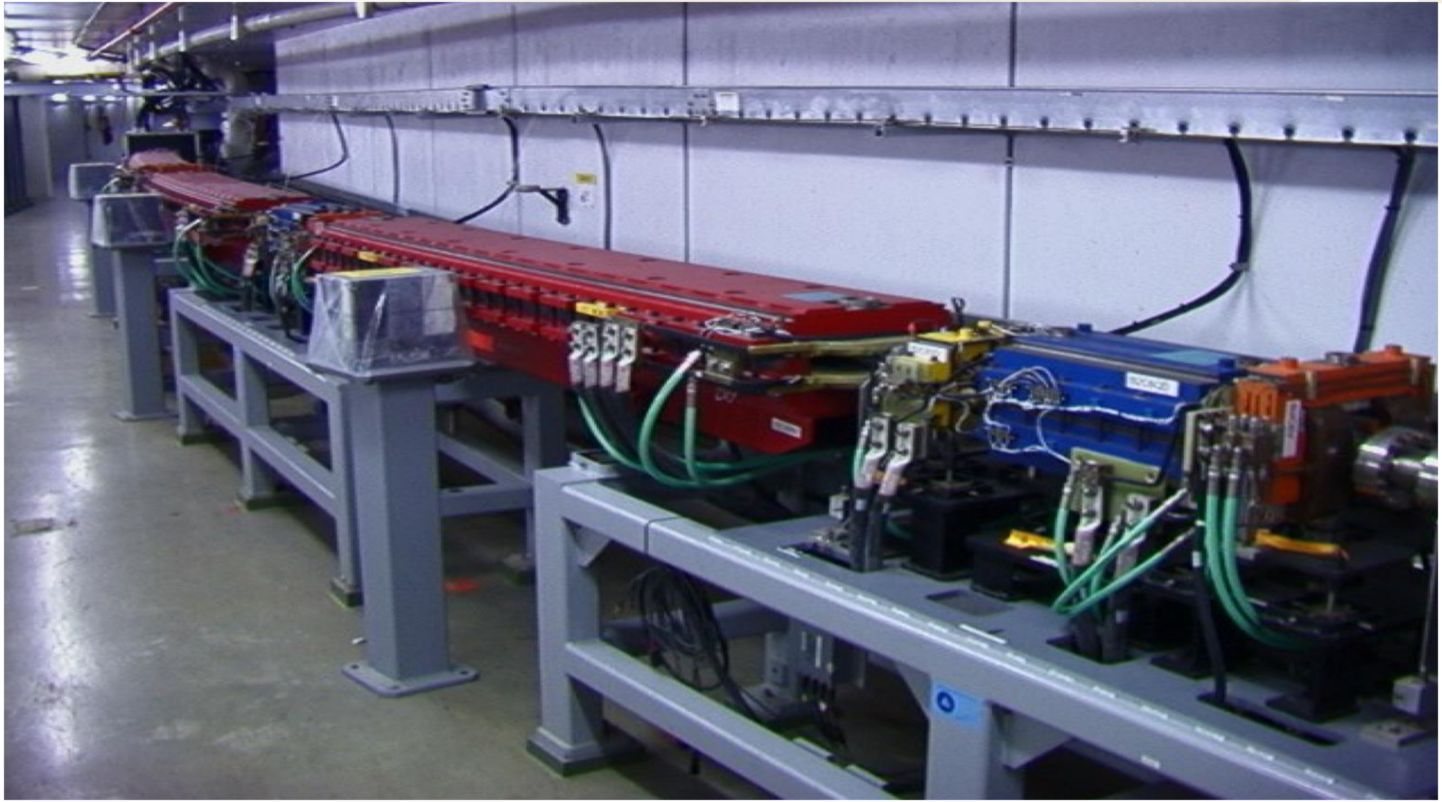


○ Beam-pipe in center of symmetry of magnet aperture

$$B_y[\mathrm{T}] = \frac{0.4\,\pi}{10^4}\,\frac{I[\mathrm{A-turn}]}{G[\mathrm{cm}]}$$

$$\frac{1}{\rho[\mathrm{m}]} = 0.3\,\frac{B_y[\mathrm{T}]}{\beta\,E[\mathrm{GeV}]}$$

Bending Magnets in the APS Ring



APS Magnets Awaiting Installation

Superconducting Magnets

1232 bending magnets 15m
NbTi cables, 13 кA@1.9 K 10 GJ

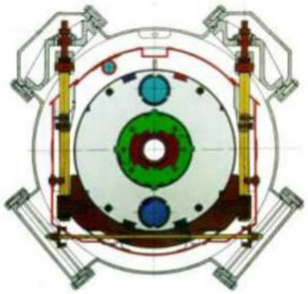
4.5T

Tevatron,
6 m, 76 mm
774 dipoles

4.5 K He, NbTi
+ warm iron
small He-plant

5.3T

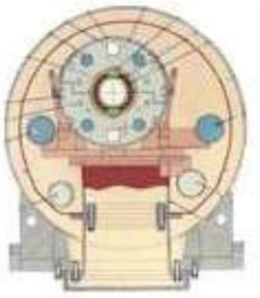
HERA,
9 m, 75 mm
416 dipoles



NbTi cable
cold iron
Al collar

3.5T

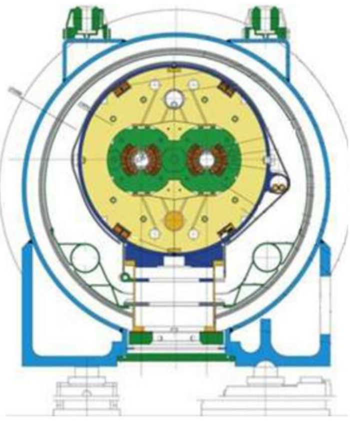
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

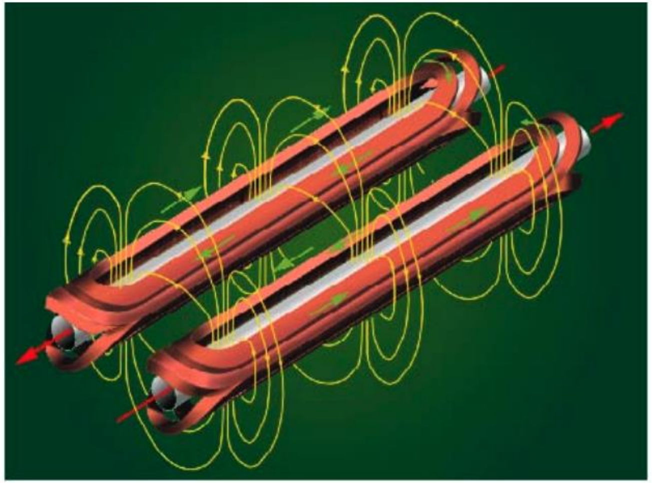
8.3T

LHC,
15 m, 56 mm
1276 dipoles



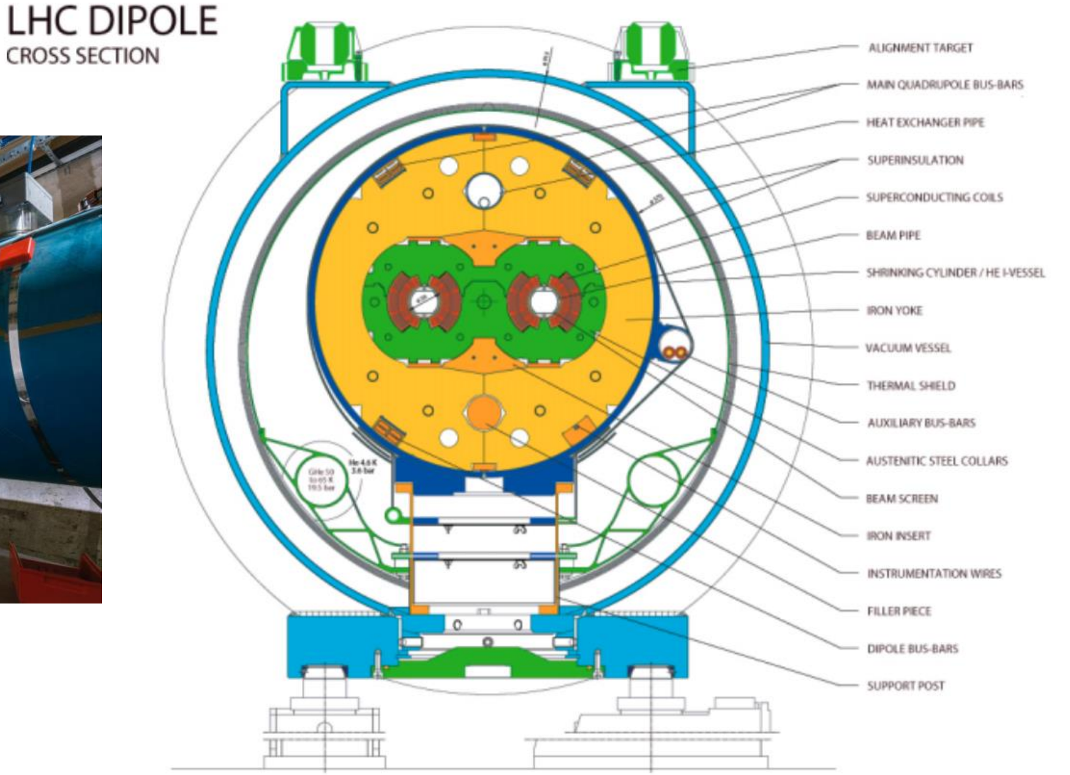
NbTi cable
2K He
two bores

Dipole Field Produced by SC Tape



LHC Superconducting Magnets

LHC Dipole in Tunnel

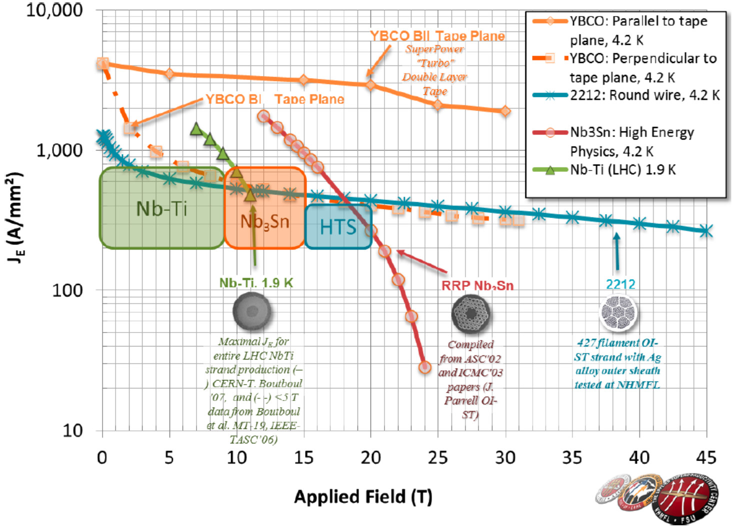


CERN AC/DI/MM — 06-2001

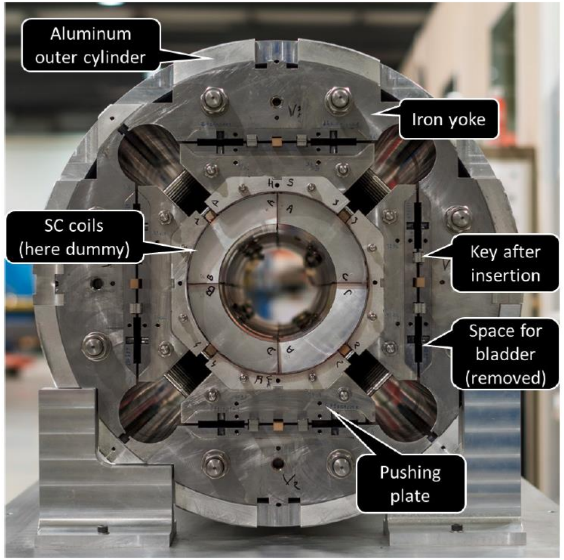
Path Forward for Superconducting Magnets

- Magnet performance will determine energy reach of future colliders
- FCC-hh baseline at 16 T
- HL-LHC will also benefit from higher fields

Superconducting Wire Performance



HL-LHC Nb3Sn IT Quad



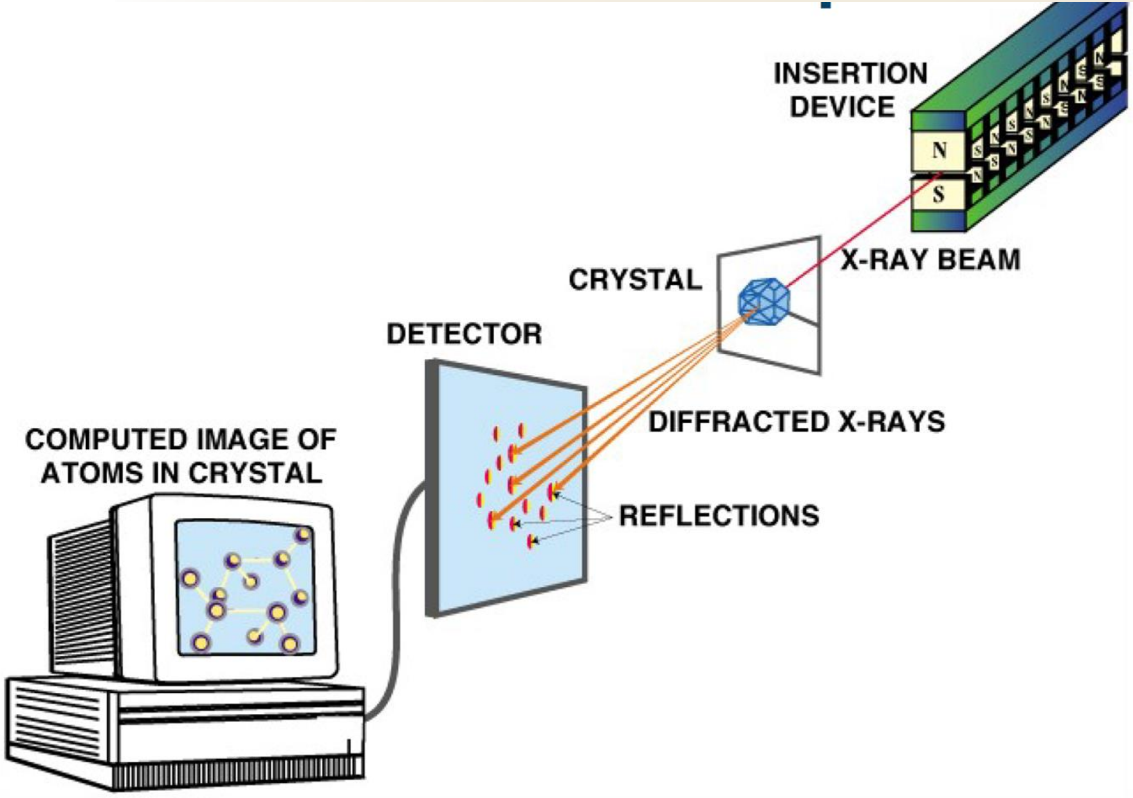
Existing quads

- 70 mm aperture
- 200 T/m gradient

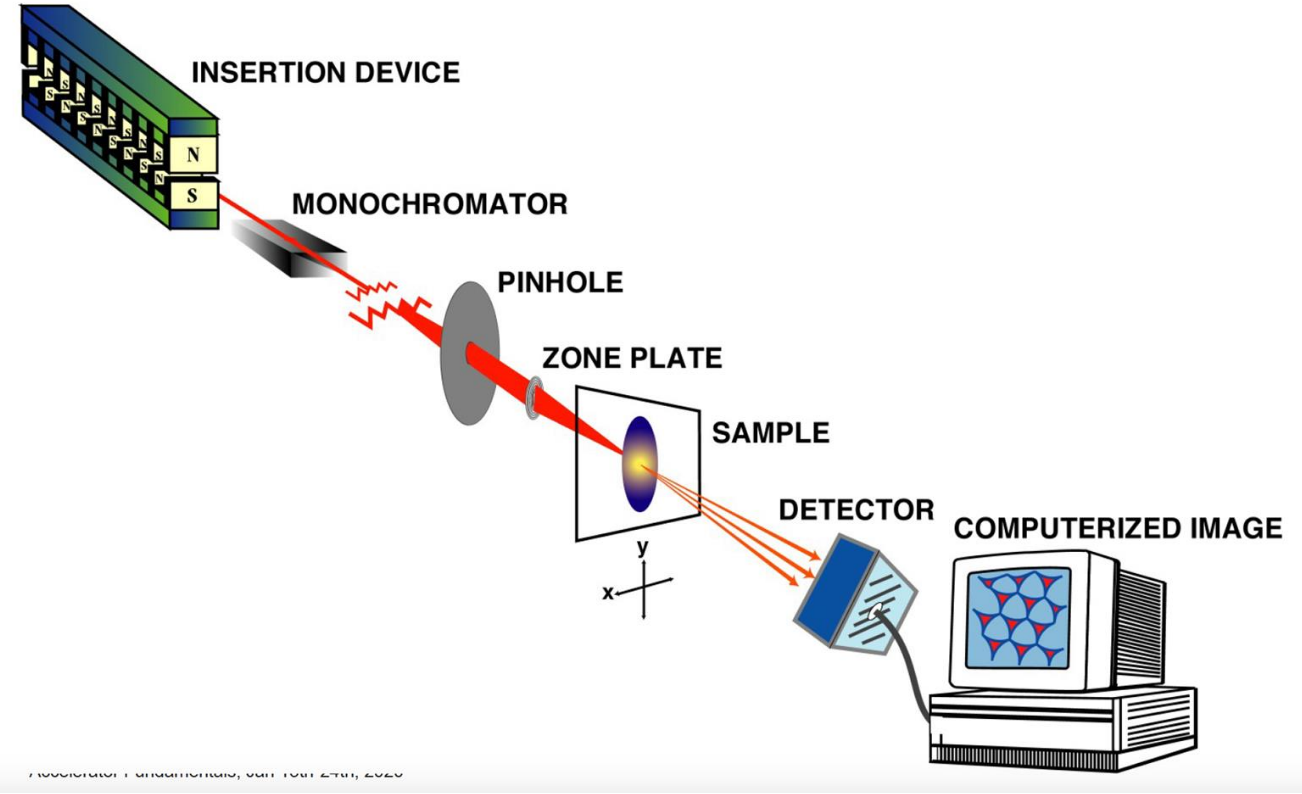
Proposed for upgrade

- At least 120 mm aperture (now 150 mm)
- 200 T/m gradient
- Field 70% higher at pole face

Applications Side – X-ray Diffraction

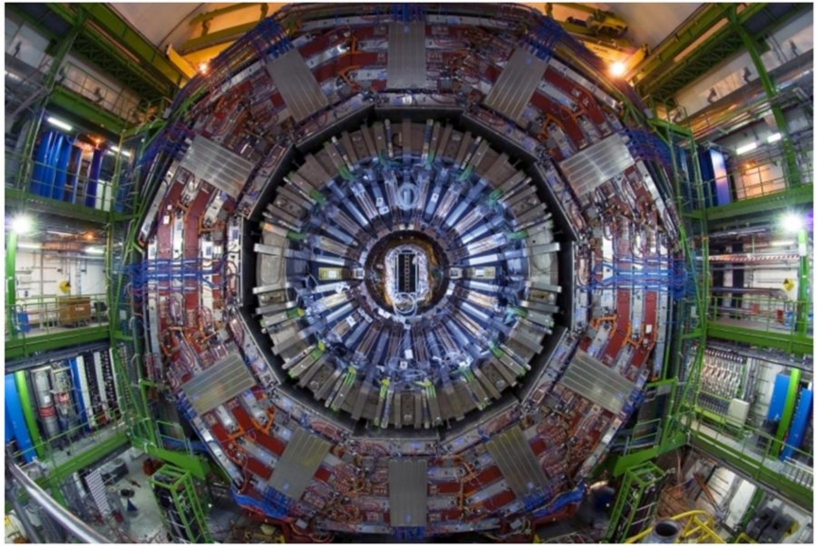


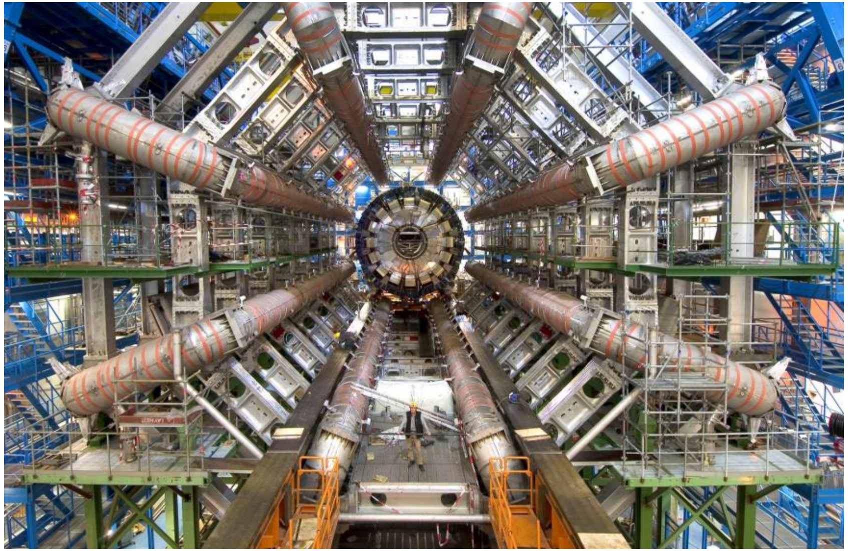
Applications Side – X-ray Imaging



Application Side: Particle Physics

CMS & ATLAS at CERN





Outline

Part II

- Basic Accelerator Physics
- Future Directions

Relativity and Units

Useful Terms:

Caution: Beta will also be used for beta function

$$\beta \equiv \frac{v}{c}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\text{Momentum } p = \gamma m v = \gamma \beta m c$$

$$\text{Total Energy } E = \gamma m c^2$$

$$\text{Kinetic Energy } K = E - mc^2 = (\gamma - 1)\, mc^2$$

$$\beta = \frac{pc}{E}$$

$$\gamma = \frac{E}{mc^2}$$

$$\beta\gamma = \frac{pc}{mc^2}$$

<u>Units:</u>

Will use SI units, except
Energy: eV (keV, MeV, etc) [1 eV= 1.6x10^{-19}J]
Mass: eV/c^2 [proton = 1.67x10^{-27}kg = 938 MeV/c^2]
Momentum: eV/c [proton @ β=.9 = 1.94 GeV/c]

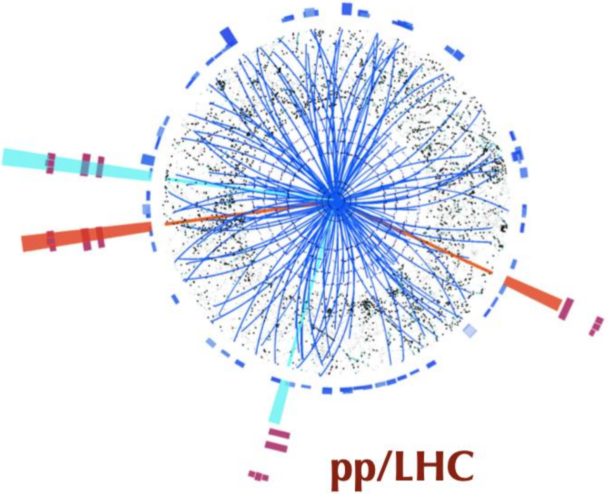
Protons vs. Electrons

Protons are made of quarks and gluons

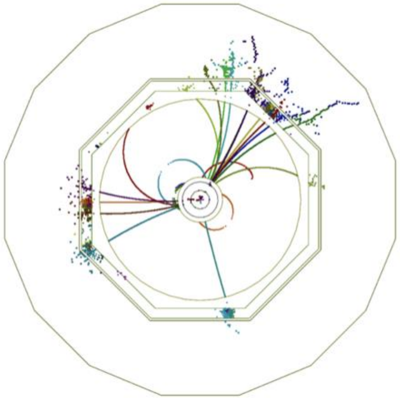
- Interaction takes place between these constituents
- Only a small fraction of energy available, not well-defined
- Rest of particle fragments

Electrons are fundamental point-like particles

- Well-defined initial state
- Full energy available to interaction
- Clean interaction environment



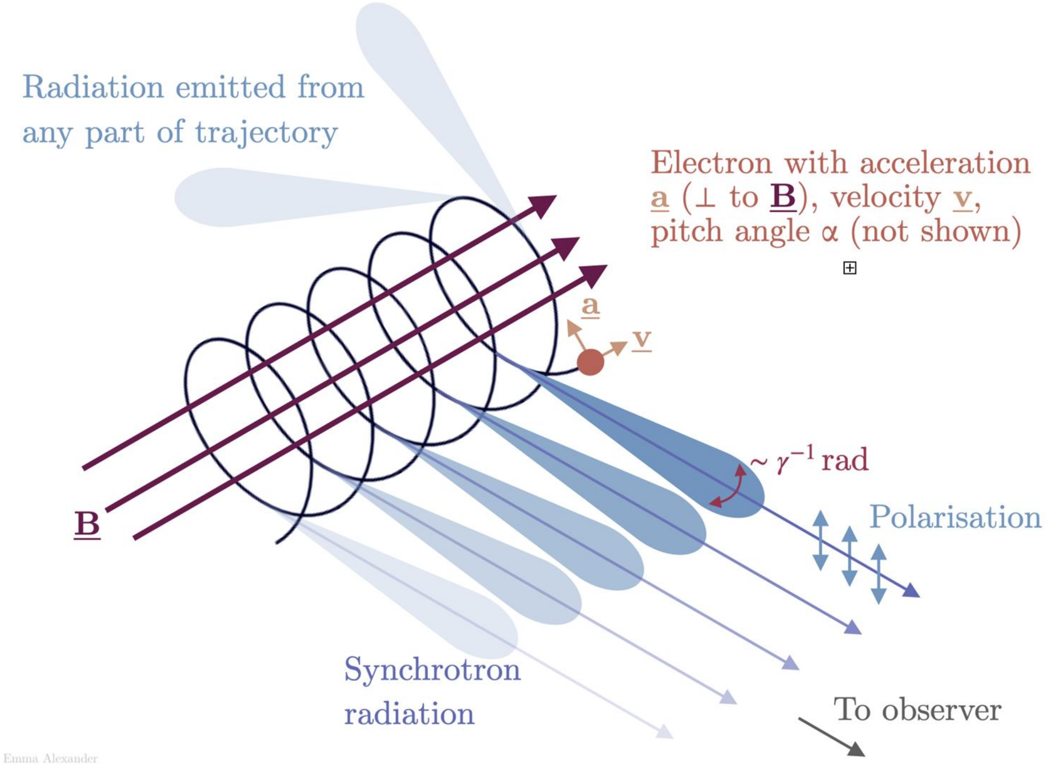
pp/LHC



e^+e^-

Why don’t we only use electrons?

Synchrotron Radiation



$$P_\gamma = \frac{1}{6\pi\varepsilon_o}\frac{q^2 a^2}{c^3}\gamma^4$$

$$\propto \frac{1}{\rho^2}\left(\frac{E}{m}\right)^4$$

ε_o is the vacuum permittivity,

q is the particle charge,

a is the magnitude of the acceleration,

c is the speed of light,

γ is the Lorentz factor.

https://en.wikipedia.org/wiki/Synchrotron_radiation

Circular Accelerators

- Use magnetic field to guide charge particles in a closed orbit
- Acceleration is done by rf cavities (except for betatron)
- rf cavities traversed many times, simplifying rf systems
- For electrons circular accelerators are limited in energy due to synchrotron radiation – 100 GeV of LEP (27 km)
  - An electron will radiate about ***10^{13} times more power*** than a proton of the same energy!!!! (For LHC in W/m range)
- Need linear accelerators for arbitrary high energy
- For protons or ions, circular accelerators are ideal for reaching high energies, 1 TeV at Fermilab (6 km), 7 TeV for LHC (27 km)
- Very large ring (FCC-ee/CEPC) for a e+e- Higgs factory – energy loss per turn 10-20 GeV

Understanding Beam Motion: Beam “Rigidity”

The relativistically correct form of the Lorentz force for a particle in an electromagnetic field is:

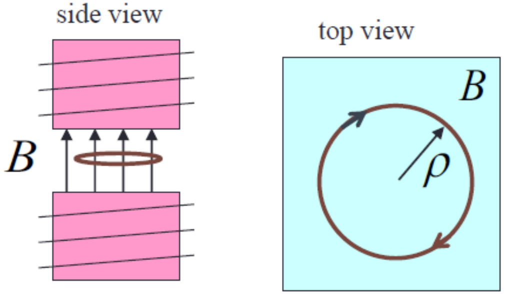
$$\vec{F} = \frac{d\vec{p}}{dt} = q(\vec{E} + \vec{v} \times \vec{B})$$

$$\vec{p} \equiv \gamma m \vec{v}$$

A particle of charge *q* in a uniform magnetic field will move in a circle of radius

$$\rho = \frac{p}{qB}$$

$$p\,[\frac{GeV}{c}] \approx 0.3\,B[T]\rho[m] \qquad B\rho = \frac{p}{q}$$



Beam “rigidity” = constant at a given momentum

If all magnetic fields are scaled with the momentum as particles accelerate, the trajectories remain the same ▯“synchrotron” [E. McMillan, 1945]

Example Beam parameters

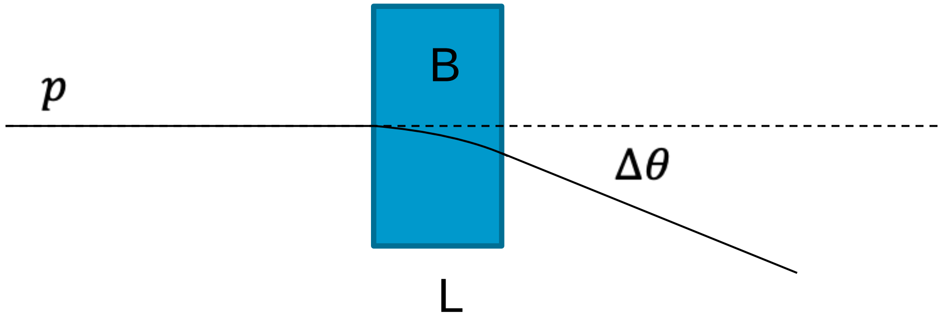
- Compare CERN Linac4 (K=160 MeV) to LHC (K=7000 GeV)

Parameter	Symbol [Unit]	Equation	Injection	Extraction
Proton Mass	m [GeV/c2]		0.938	
Kinetic Energy	K [Gev]		0.16	7000
Total Energy	E [GeV]	$K+mc^2$	1.098	7000.938
Momentum	p [GeV/c]		0.571	7000.938
Rel. Beta		(pc)/E	0.520	1.000
Rel. Gamma		$E/(mc^2)$	1.171	7463.687
Beta-Gamma		$(pc)/(mc^2)$	0.608	7463.687
Rigidity		p [GeV/c] / 0.3	1.904	23352.028

Radius of curvature in meters for 1 T field ***or*** magnetic field in Tesla for one meter radius of curvature

Thin Lens Approximation and Magnetic "kick"

- For bending magnets, the length of the magnet is typically short compared to the bending radius
- The particle receives a transverse "kick", which is proportional to the integrated field
- Results in a small bend angle

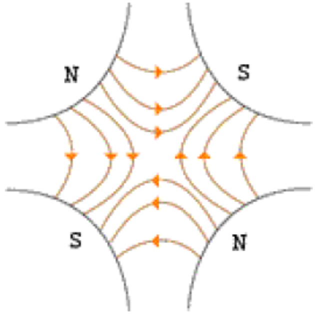


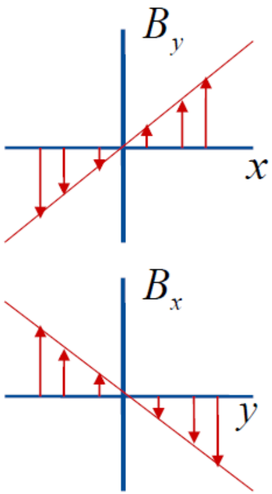
$$p_\perp = qvBt = qvB\,L/v = qBL$$

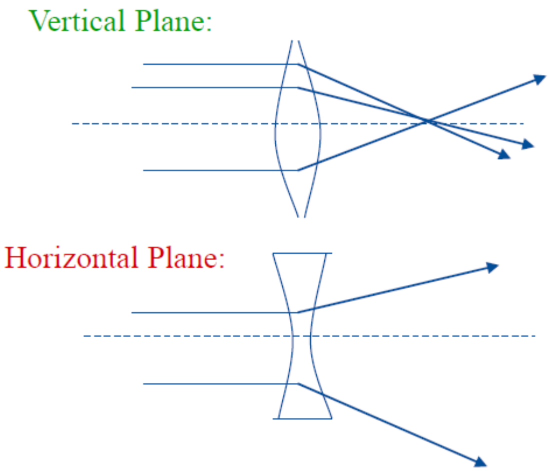
$$\Delta\theta \approx \frac{p_\perp}{p} = \frac{qBL}{qB\rho} = \frac{BL}{(B\rho)}$$

Focusing the Proton Beam

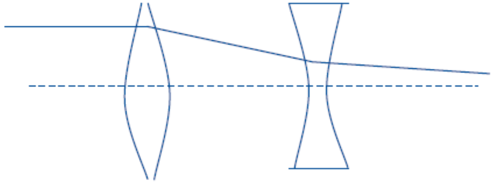
- Transverse field with a gradient provides focusing/defocusing

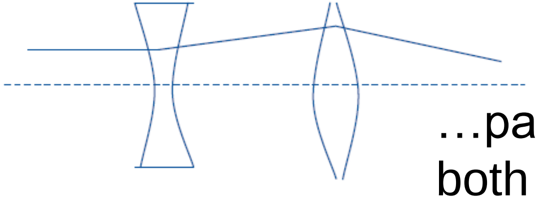






Luckily…





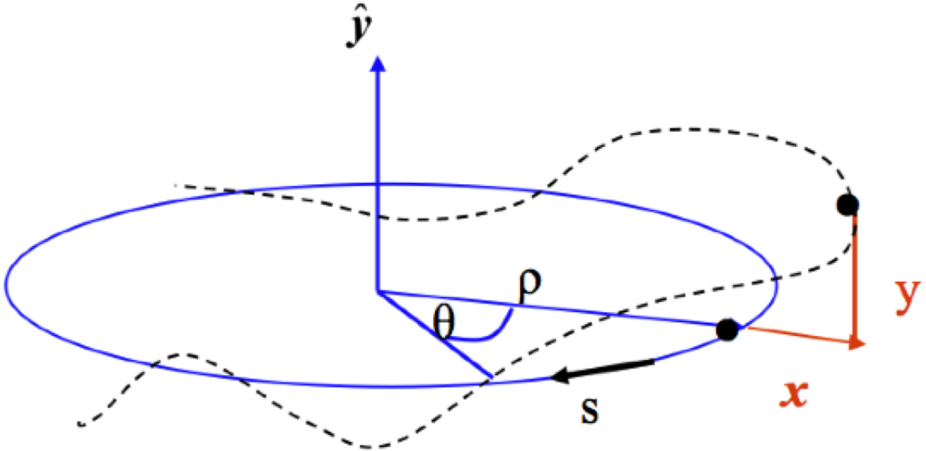
…pairs give net focusing in both planes! -> “FODO cell”

Equation of Motion

- Not all particles follow the "ideal" circular orbit
- Use a coordinate frame referenced with respect to "ideal"
- We are interested in the linear forces affecting the beam orbit

$$F_r = m\,a_r = eB_y v$$

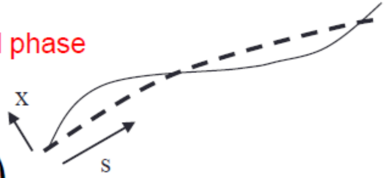
$$\frac{B_y(x)}{p/e} \approx \frac{1}{\rho} + k\,x$$



Betatron Oscillation

- “Quasi-harmonic” motion around the “ideal” orbit
- “Beta function”, determined by the focusing properties of the lattice

Position dependent amplitude and phase



Lateral deviation in one plane

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

Phase advance

$$\psi(s) = \int_0^s \frac{ds}{\beta(s)}$$

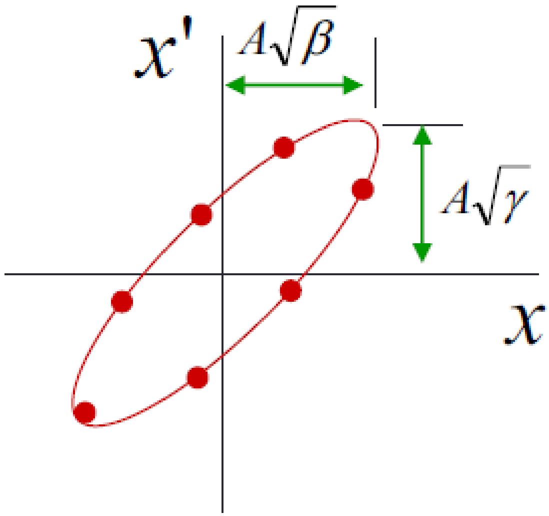
The “betatron function” $\beta(s)$ is effectively the local wave number and also defines the beam envelope.

Closely spaced strong quads -> small β -> small aperture, lots of wiggles

Sparsely spaced weak quads -> large β -> large aperture, few wiggles

Particle Behavior Over Multiple Turns

- Particle returns to the same location (*s*) with a different phase advance
- Over many turns the particle will define an ellipse

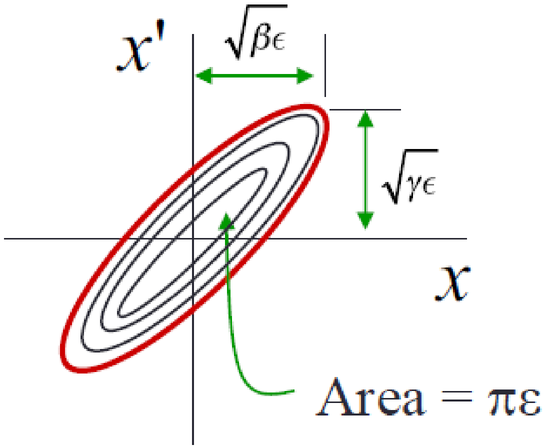


$$\gamma x^2 + 2\alpha x x' + x'^2\beta = A^2$$
$$\mathrm{Area} = \pi A^2$$
$$\beta\gamma - \alpha^2 = 1$$

Particle will return to a *different* point on the *same* ellipse each time around the ring.

Emittance Characterizes the Ensemble

If each particle is described by an ellipse with a particular amplitude, then an ensemble of particles will always remain within a bounding ellipse of a particular area:



$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon$$

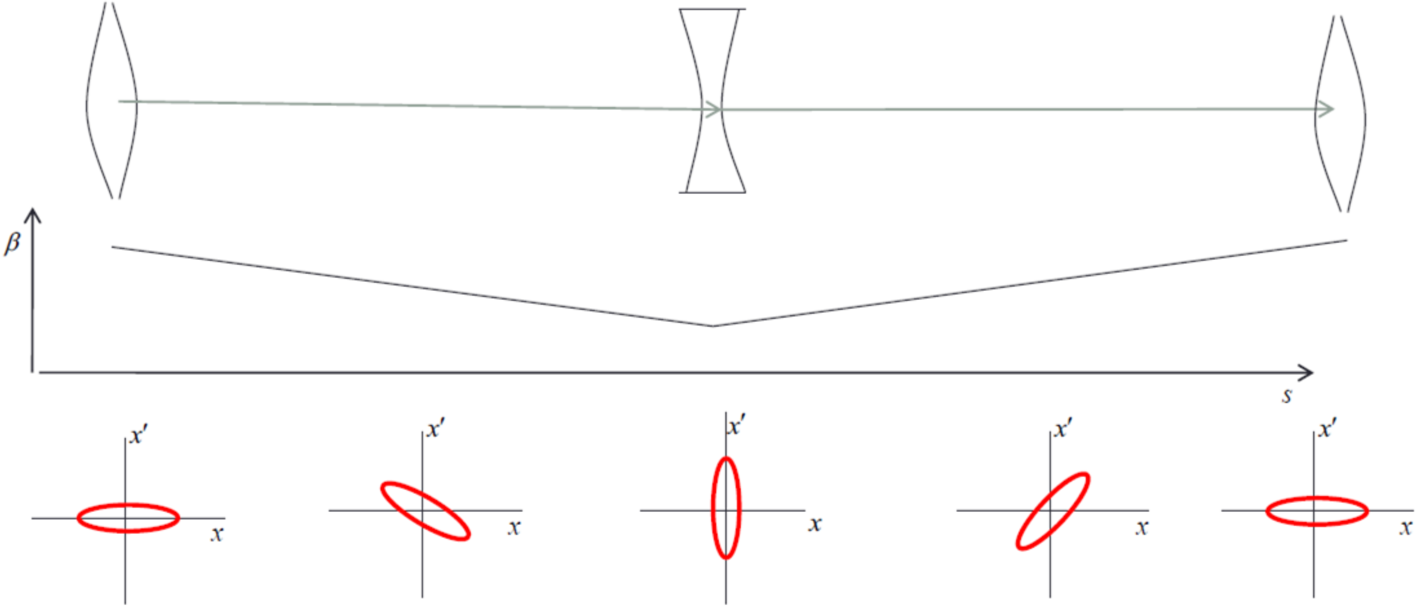
There are different definitions of emittance, but CERN generally uses the Gaussian definition

$$\varepsilon = \frac{\sigma_x^2}{\beta_x};\ \text{contains 68\% of the beam}$$

$$\rightarrow \sigma_x = \sqrt{\beta_x \varepsilon}$$

Emittance and Beam Distributions

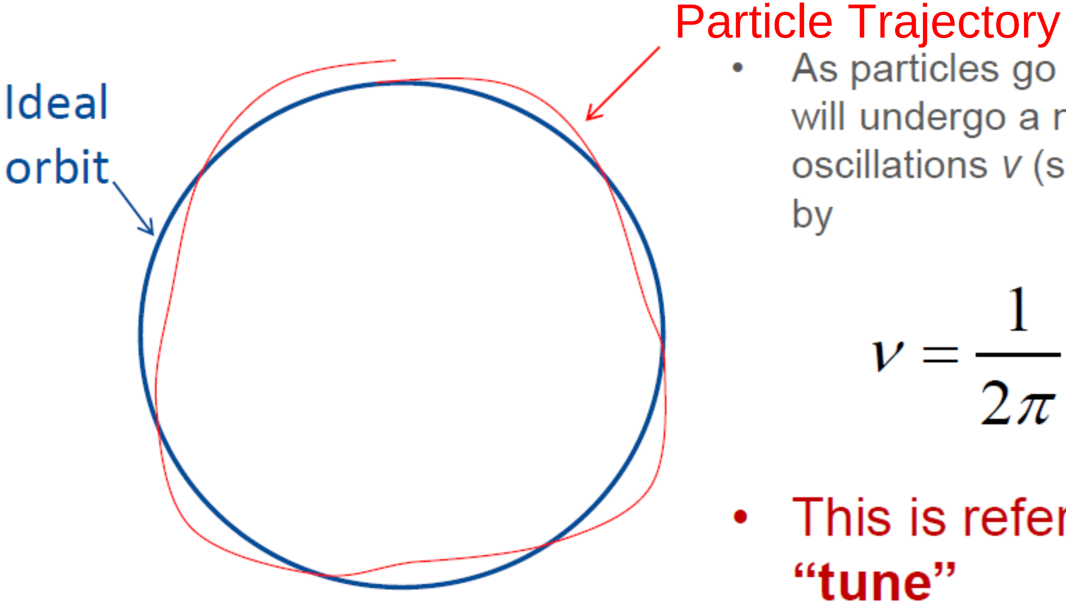
- As we go through a lattice, the bounding emittance remains constant



large spatial distribution
small angular distribution

small spatial distribution
large angular distribution

Betatron Oscillation and Tune



- As particles go around a ring, they will undergo a number of betatron oscillations *ν* (sometimes Q) given by

$$\nu = \frac{1}{2\pi}\oint \frac{ds}{\beta(s)}$$

- This is referred to as the **"tune"**

We generally consider the tune in two parts:

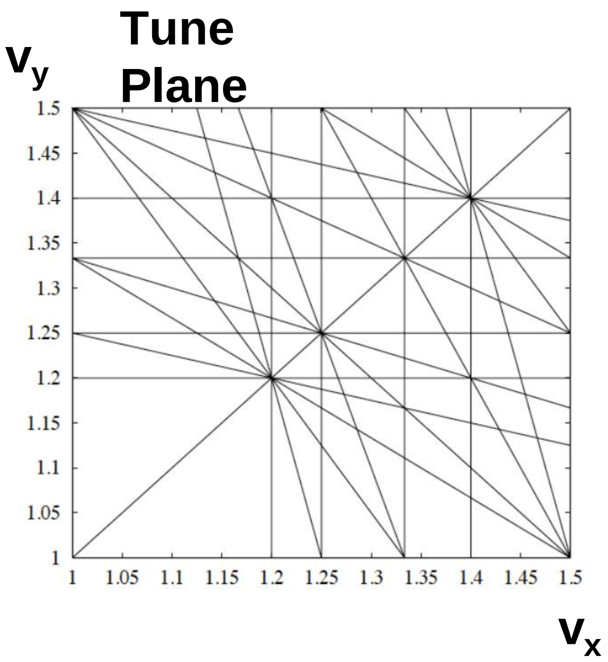
Integer : magnet/aperture optimization ↗ 6.7 ↖ Fraction: Beam Stability

Tune, Stability, and the Tune Plane

- If the tune is an integer, or low order rational number, then the effect of any imperfection or perturbation will tend be reinforced on subsequent orbits.
- When we add the effects of coupling between the planes, we find this is also true for combinations of the tunes from both planes, so in general, we want to avoid

$$k_x v_x \pm k_y v_y = \text{ integer} => \text{resonant instability}$$

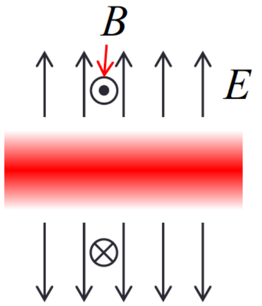
- Many instabilities occur when something perturbs the tune of the beam, or part of the beam, until it falls onto a resonance, thus you will often hear effects characterized by the "tune shift" they produce.


Tune Plane

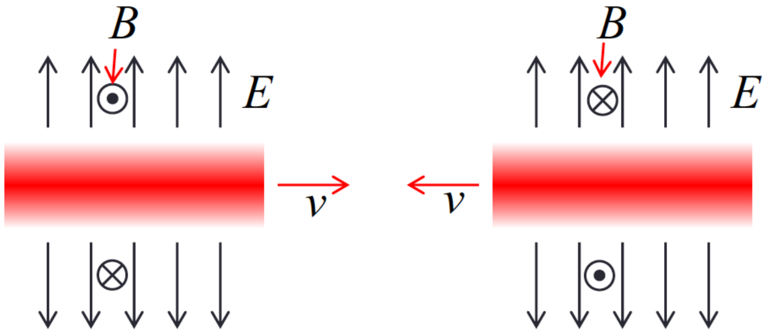
Tune Shift and Instabilities

- The beam will go unstable if the tune is shifted onto a harmonic instability

- Space charge tune shift
  - Affects circulating beams
  - The repulsion of the other particles in the bunch defocuses the beam, lowering the tune.
  - Effect falls rapidly with energy, which is why the bunch intensity at highest energies is typically limited very early in the accelerator chain
- Beam-beam tune shift
  - When a bunch passes through another it will be defocused (focused) for same (opposite) sign particles, decreasing (increasing) the
  - This is the ultimate limitation to luminosity in colliders



E and B only balanced when $\beta = 1$; otherwise repulsive



Fixed Target Colliders – LBL Bevatron


Ed McMillan and Ed Lofgren

-Last and largest weak-focusing proton synchrotron
-1954, Beam aperture about 4’ square!, beam energy to 6.2 GeV
-Discovered antiproton 1955, 1959 Nobel for Segre/Chamberlain

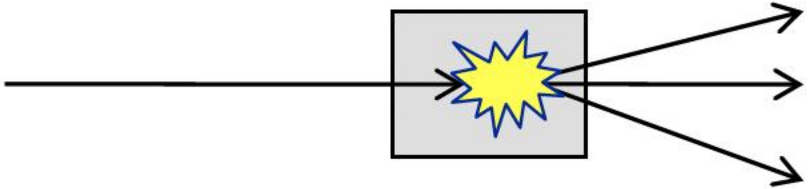
Static vs. Head-On

Anti-proton production: Why did the Bevatron need 6.2 GeV?

Anti – protons. are “only”930 MeV/c2(times 2…)

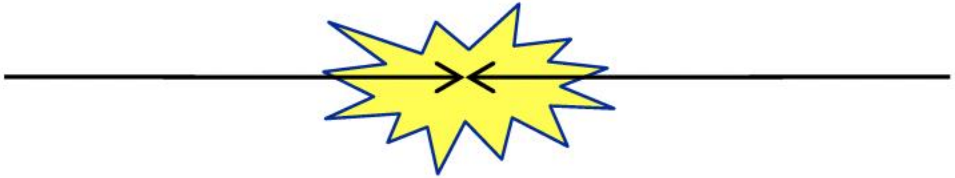
Bevatron used Cu target: p + n →p + n + p + pbar

$$E_{cm} = \sqrt{2(\gamma + 1)}m_p c^2$$



If both beams have same momentum…

$$E_{cm} = 2\gamma m_p c^2\text{=2E}$$



Luminosity of Colliding Beams

- Equally intense Gaussian beams

Particles per Bunch

Number of Bunches

Geometric Factor
- crossing angle
- hourglass effect

$$L = f_{rev} n_b \frac{N_b^2}{4\pi\sigma^2} R$$

Revolution Frequency

Transverse Size (RMS)

- For $\sigma^2 = \frac{\beta^* \varepsilon_N}{\beta\gamma} \simeq \frac{\beta^* \varepsilon_N}{\gamma}$

Proportional to Energy

Betatron function at collision point

$$L = \frac{1}{4\pi} f_{rev} n_b \frac{N_b^2 \gamma}{\beta^* \varepsilon_N} R$$

want strong focusing

Normalized emittance

Outline

Part II

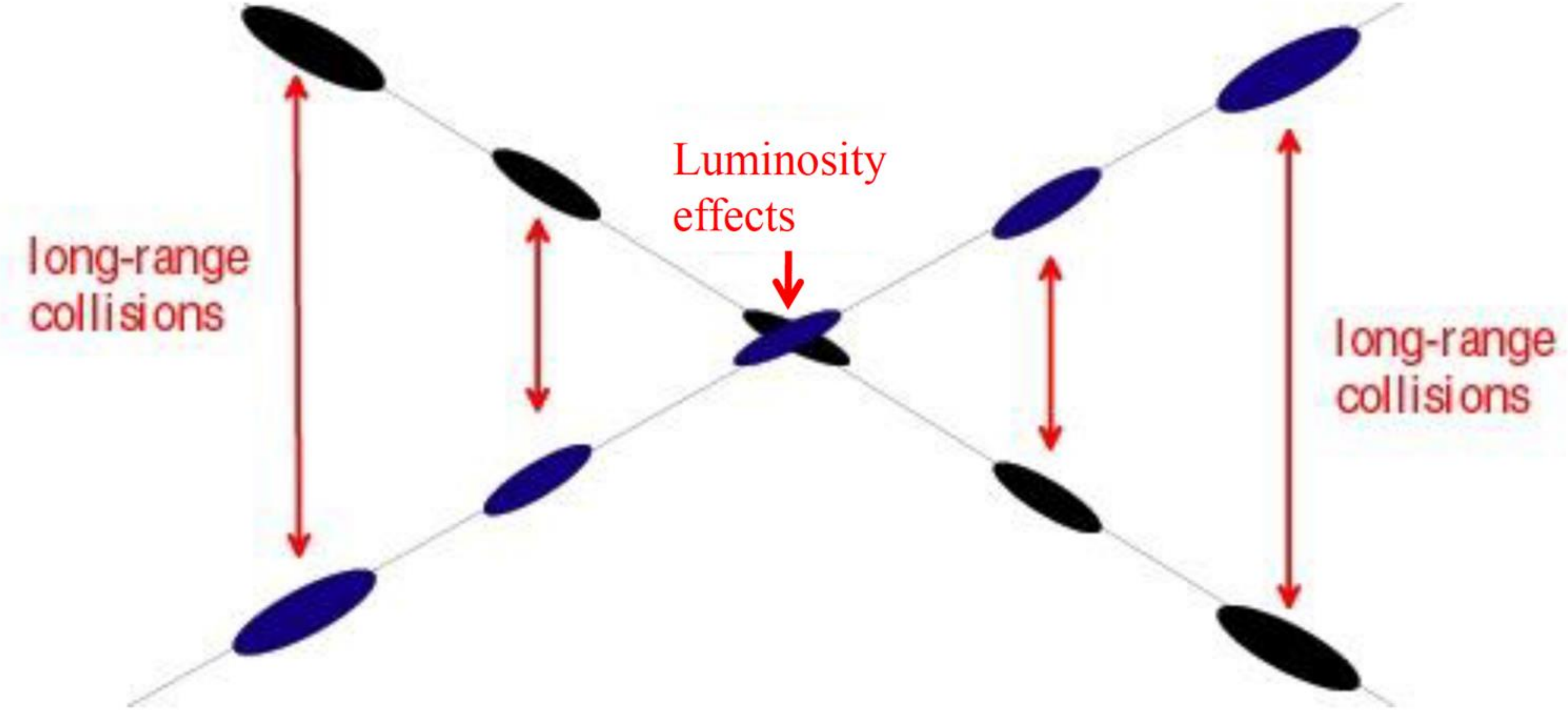
- Basic Accelerator Physics
- Future Directions

Future of LHC Research

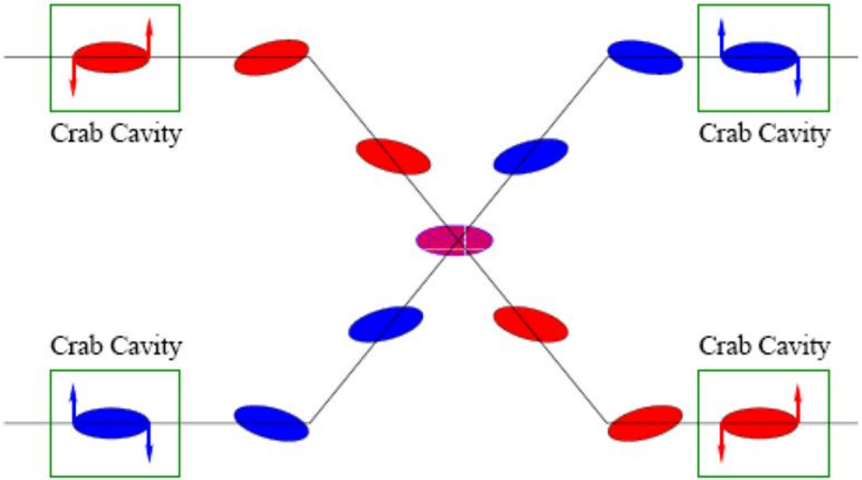
The LHC has a planned series of upgrades out to 2040 with 10-20x the current integrated luminosity

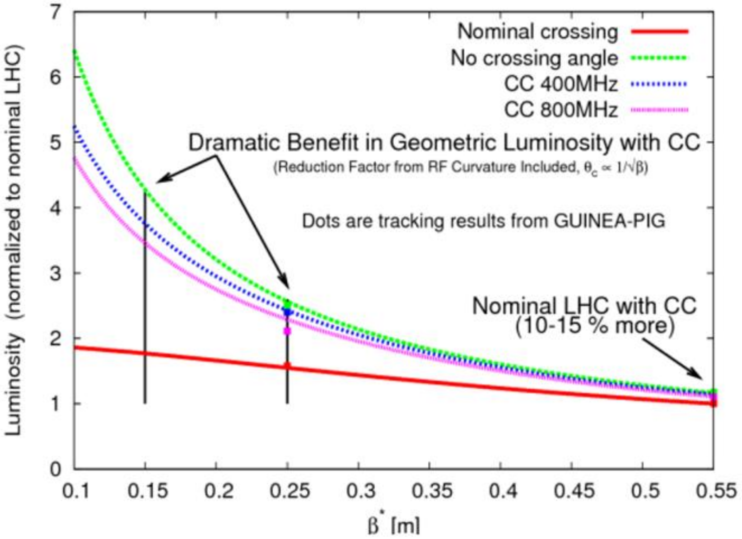
Examples: New focusing quads, upgrade to injector linac, CRAB Cavities….

Impact of Crossing Angle



Crab Cavities

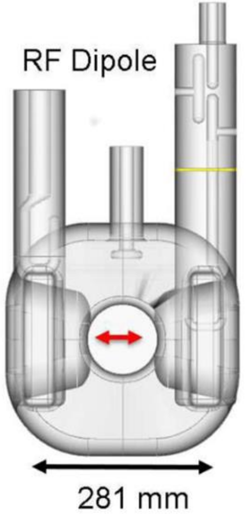


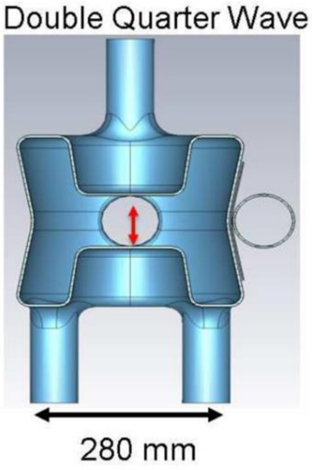


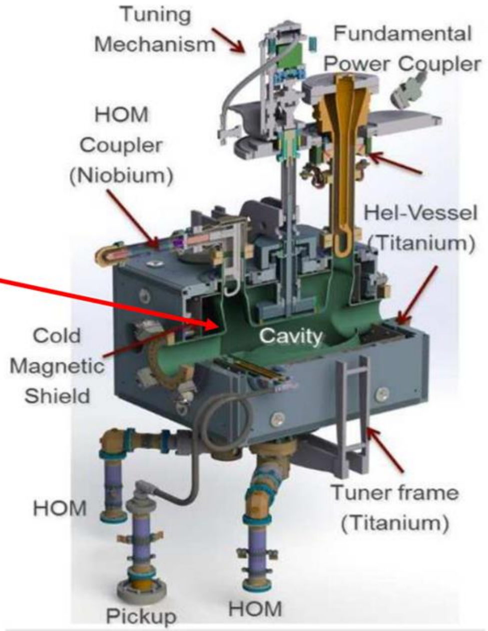
- Crab cavities apply a transverse kick so the bunches hit head on
- Challenge: need 400 MHz to prevent filamenting the bunch
  - VERY challenging to design these to fit in the ~20 cm between beam pipes!
- Long R&D program spearheaded by LARP

LHC Crab Cavities

- MANY cavities were considered, but it was finally down selected to two, one for ATLAS and one for CMS
  - One crosses vertically and one crosses horizontally







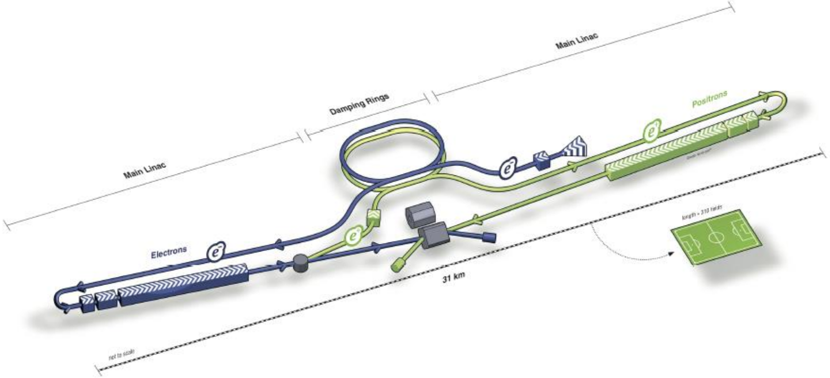
Linear vs. Circular

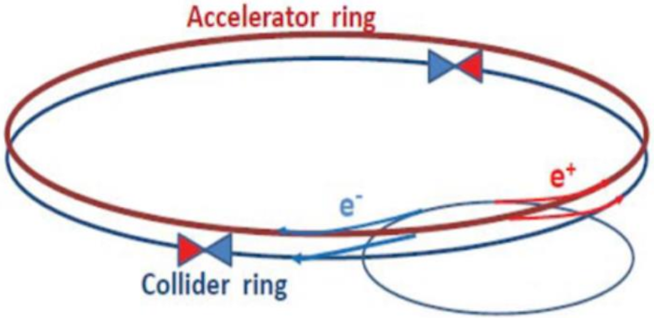
Linear e^+e^- colliders: ILC, C^3, CLIC

- Reach **higher energies** (~ TeV), and can use **polarized** beams
- Relatively low radiation
- Collisions in bunch trains

Circular e^+e^- colliders: FCC-ee, CEPC

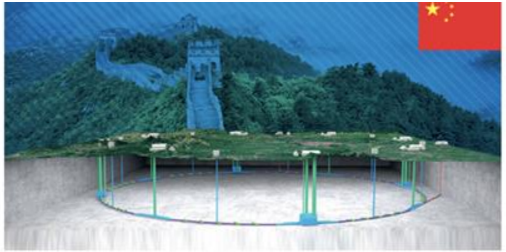
- **Highest luminosity** collider at Z/WW/Zh
- limited by synchrotron radiation above 350–400 GeV
- Beam continues to circulate after collision





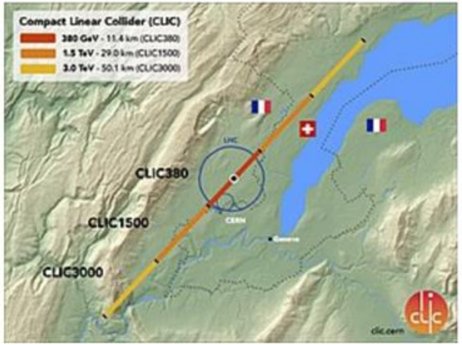
Future e^+e^- Collider Proposals….

250/500 GeV



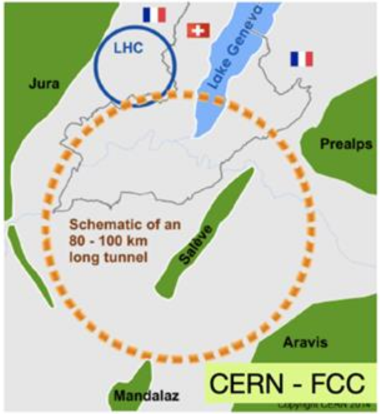
CEPC 240 GeV

CLIC 380/1500/3000 GeV



250/550 GeV

… > TeV



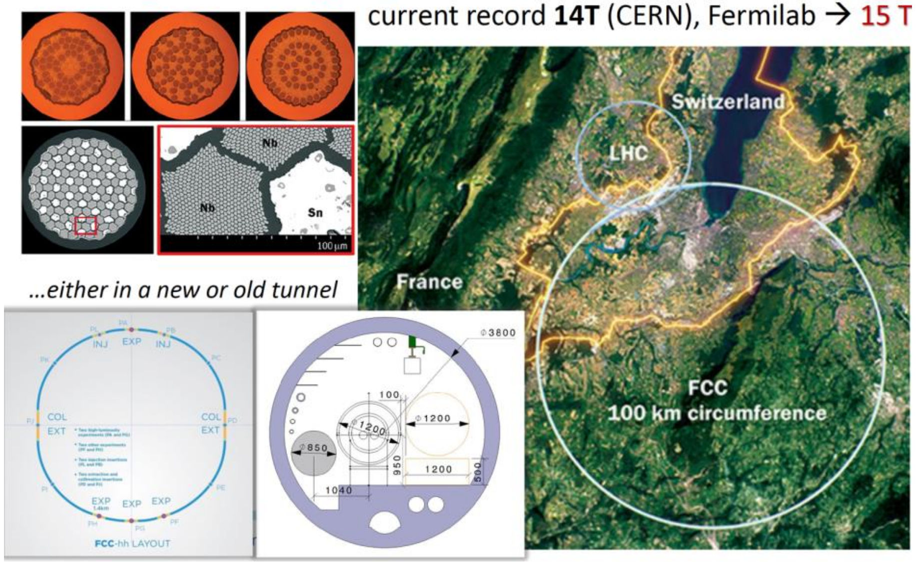
FCC-ee

240/365 GeV

Future *Muon and hh* Colliders

New magnet technology Nb_3Sn – **16 T** (vs **8 T** in the LHC with NbTi)

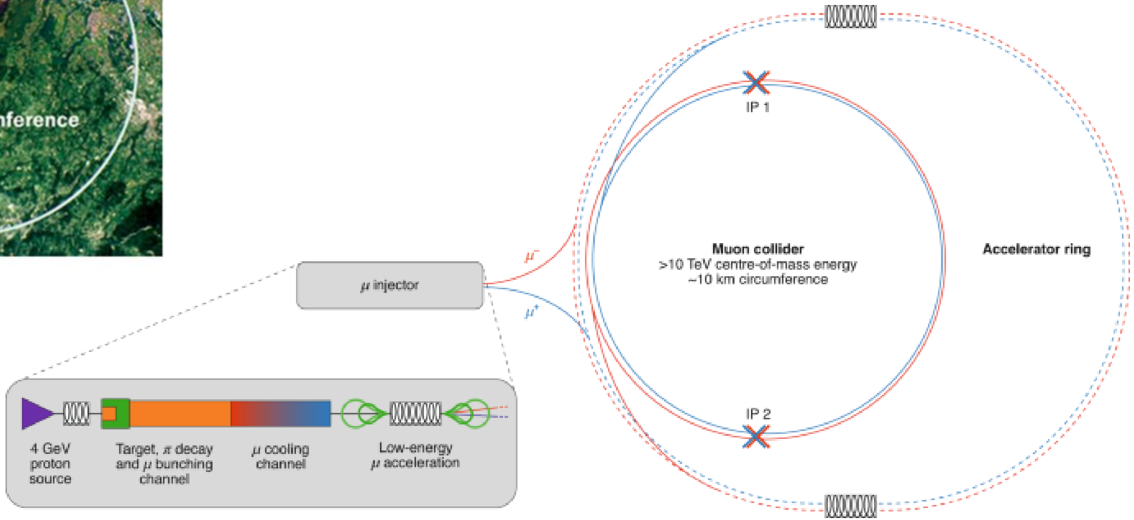
current record **14T** (CERN), Fermilab → **15 T**



...either in a new or old tunnel

FCC-hh

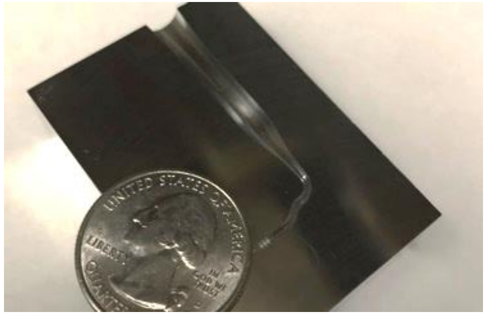
Muon Collider



Next Generation Accelerators in Pursuit of Compactness, Efficiency and Performance

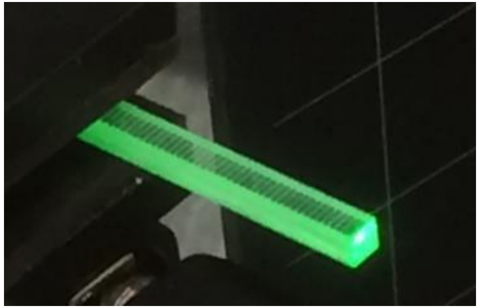
S-band Accelerators
30 MeV/m

mm-Wave/THz Accelerators
GeV/m



Klystron Source
10s MW, µs, ~3 GHz

mm-Wave/THz Sources
MW, ns, ~0.3 THz



Conclusions

- Accelerators are powerful tools for scientific discovery
- A great variety of parameters are achievable – species, power, wavelength, repetition rate
- Technology is evolving rapidly to enable new capabilities
- Opportunity to work closely with detector and user communities in developing new / improved systems
- Questions?