Introduction to Particle Accelerators

HEPIC Summer Week

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6/27/2024

U.S. DEPARTMENT OF ENERGY
Office of Science

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

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

Appendix:

- Basic Accelerator Physics
- Future Directions

Accelerator Technology Drives Scientific Discovery

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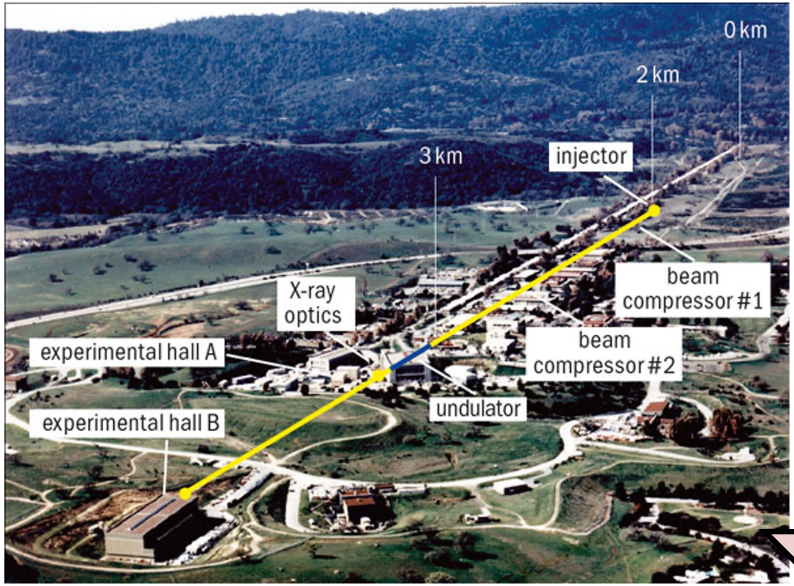
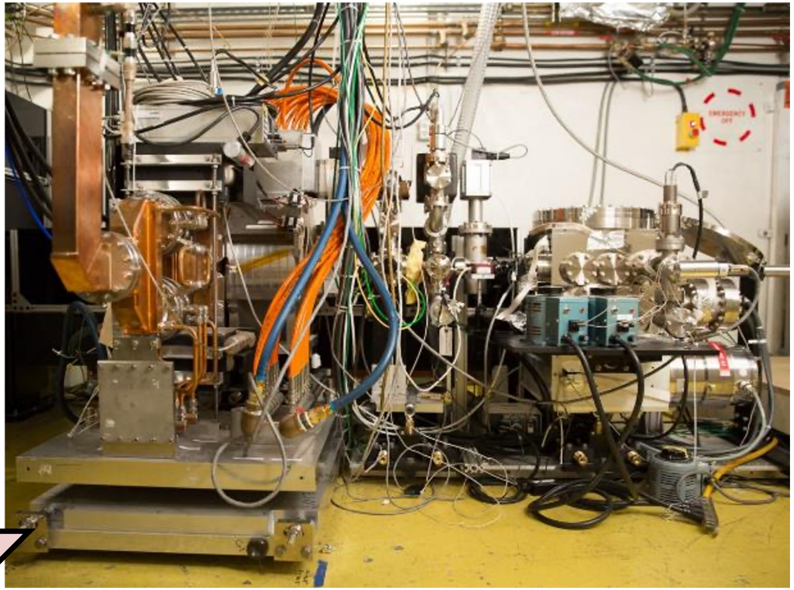
Coherent X-rays from LCLS (2009)



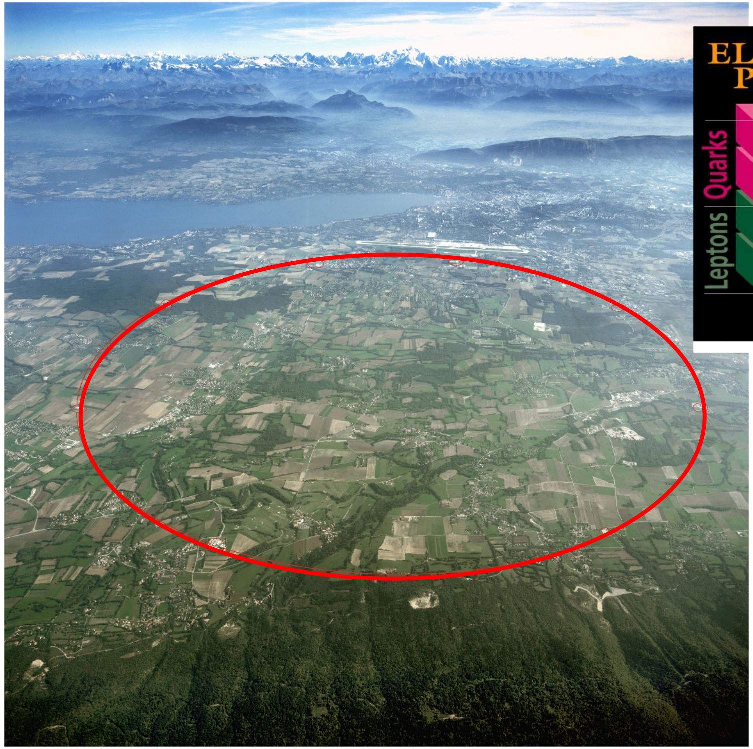
Ultrafast Electron Diffraction (2015)



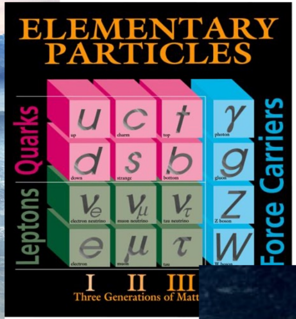
What determines the performance of an accelerator? How do accelerators work across different scales in size and energy?

RF Accelerators have been essential instruments of scientific discoveries for decades

Experimental validation of the Standard Model of Particle Physics

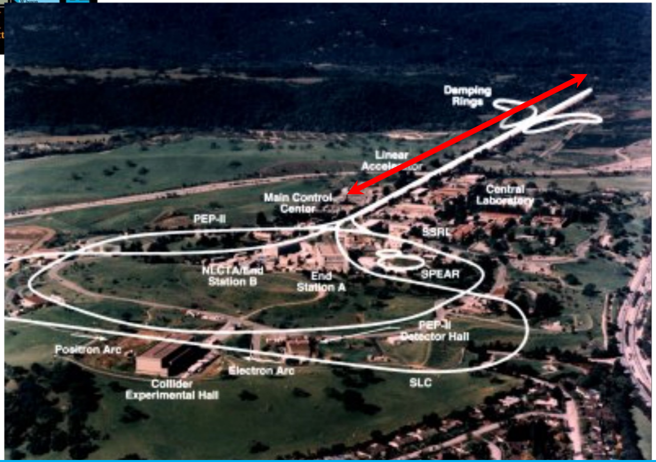


27 km LHC @ CERN



FOUR FORCES

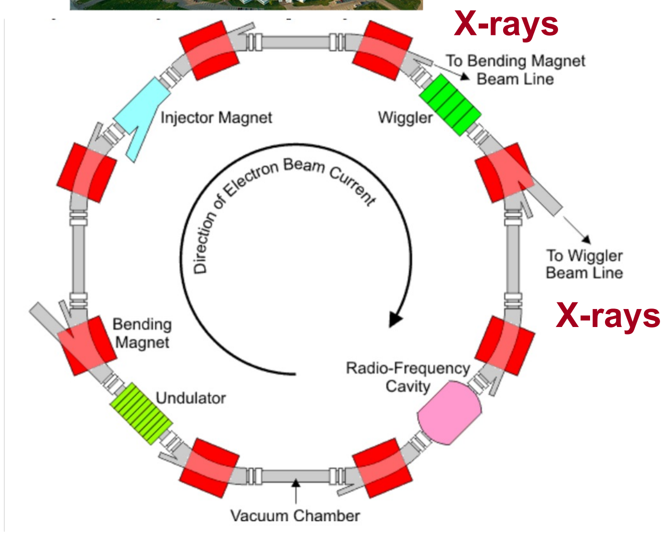
E&M
Strong
Weak
Gravity



SLAC "2 Mile" Accelerator / Collider

Accelerators have advanced other fields of science, in addition to particle physics

Particles traveling along a circular path emit synchrotron radiation



Synchrotron is a 3rd generation x-ray light source, ca. 1970s

Power radiated ~ k x Energy^4 /R^2

- X-rays for research in biology, chemistry, materials science
- US DOE operates 4 national synchrotron user facilities that are fully subscribed
- Stellar record of discoveries
- Radiation is incoherent and peak brightness is low. (more like a dim flashlight)

Why X-Rays and how do we push the frontier of x-ray science?

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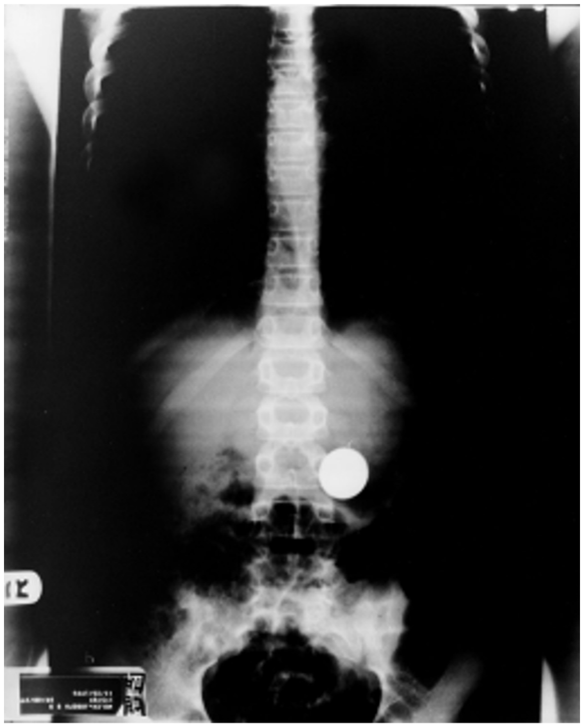
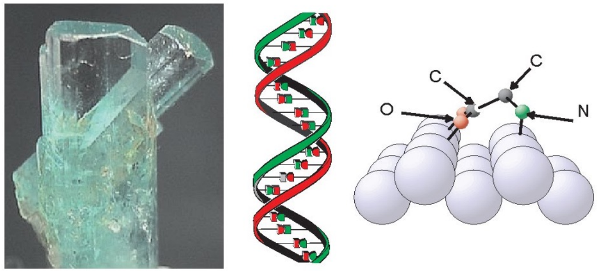
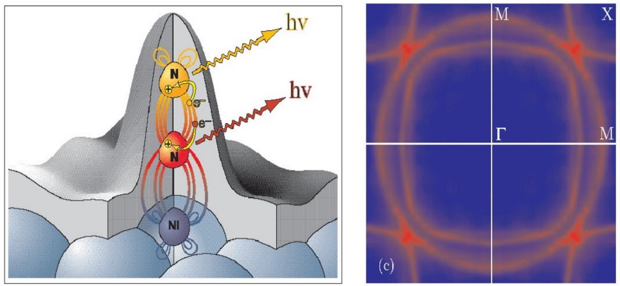
See through matter



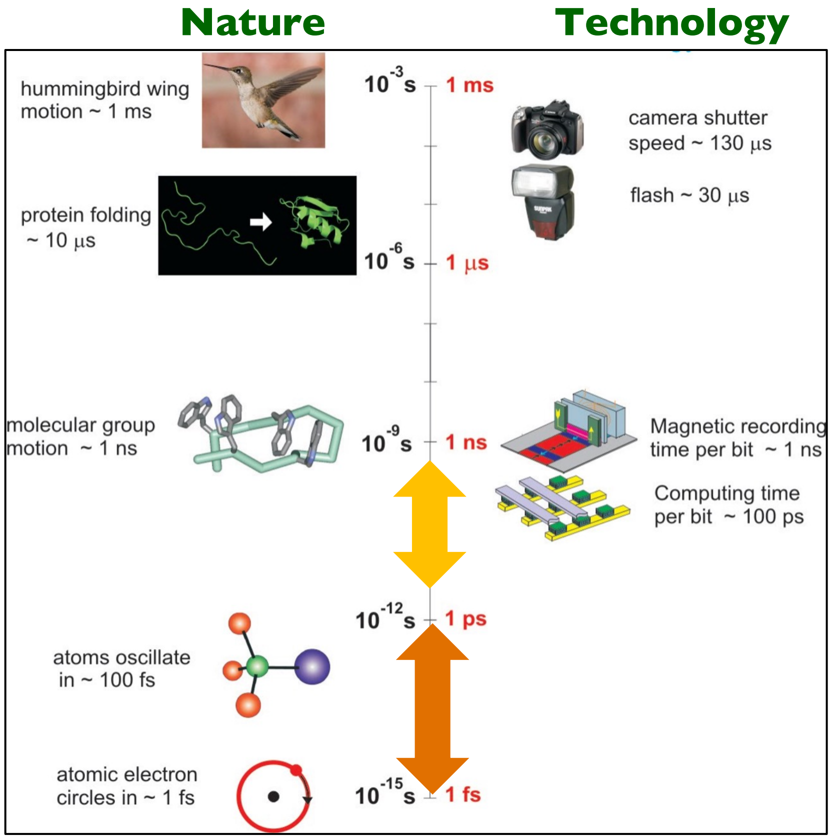
Where are the atoms?

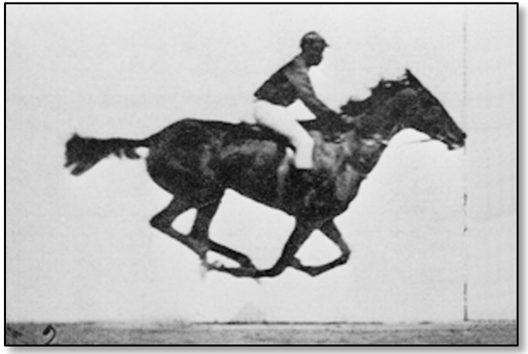


Where are the electrons?

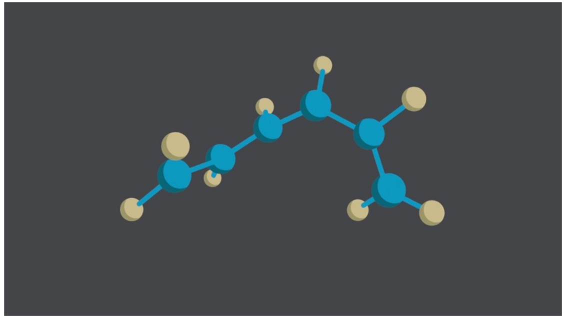


Ultra-fast and Ultra-small: The New Frontier





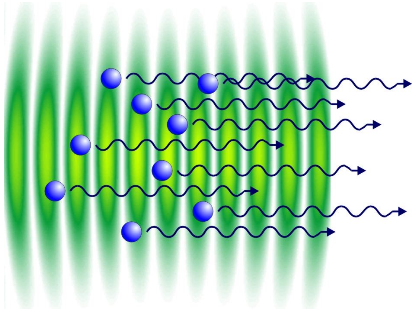
1 msec shutter speed



10-100 femtosecond shutter speed

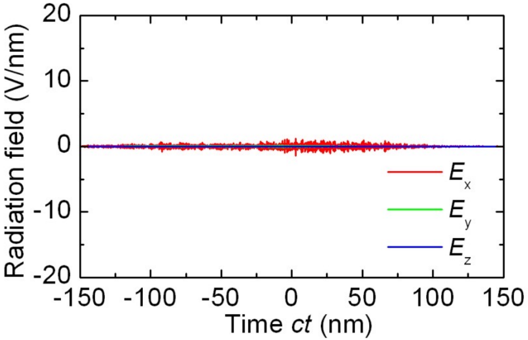
Structure (Bunching) in the Electron Beam for Coherence

ICS - Randomly distributed electrons in bunch

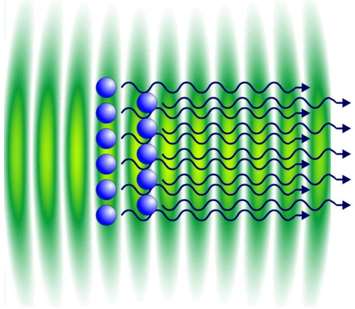


Regular:

$I_{x\text{-ray}} \sim N$



Bunched electrons

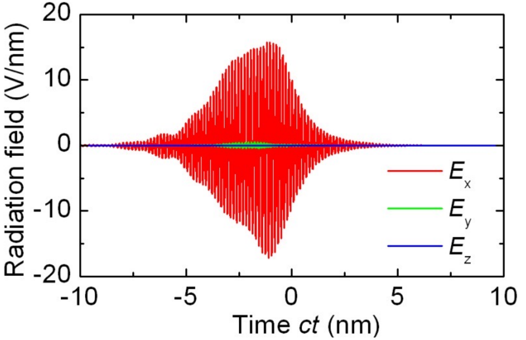


Coherent:

$I_{x\text{-ray}} \sim N^2$

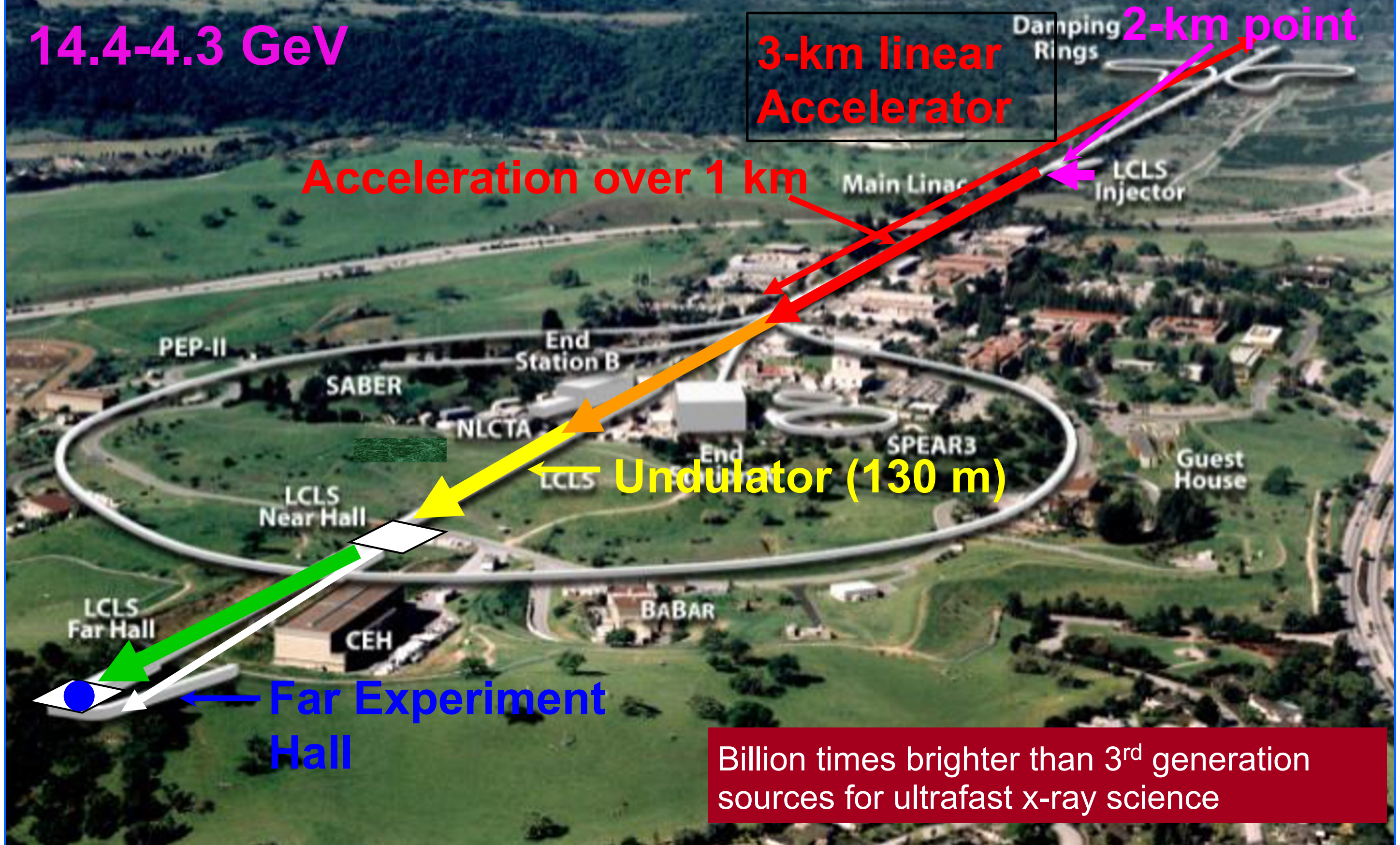
$E_{x\text{-ray}} \sim N$

$N > 10^6 - 10^8$



Linac Coherent Light Source at *SLAC*

LCLS –first x-ray free-electron laser (XFEL) using last 1-km of existing 3-km linac

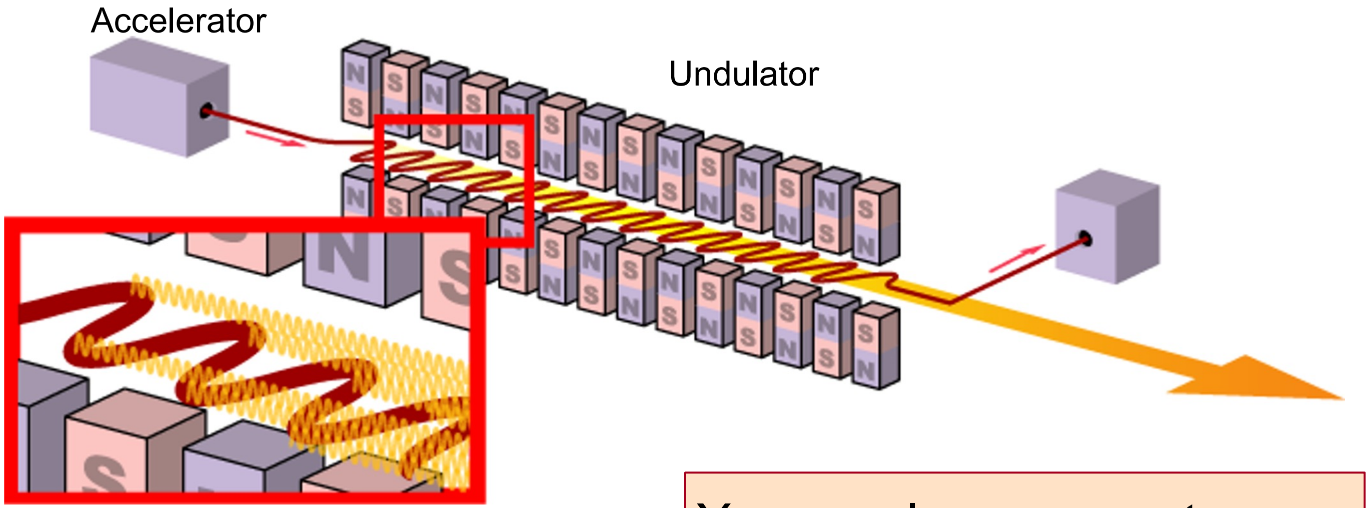


Billion times brighter than 3rd generation sources for ultrafast x-ray science

SLAC

A Free Electron Laser is a High Energy (5-12 GeV) Electron Linac Coupled to an Undulator Magnet

SLAC

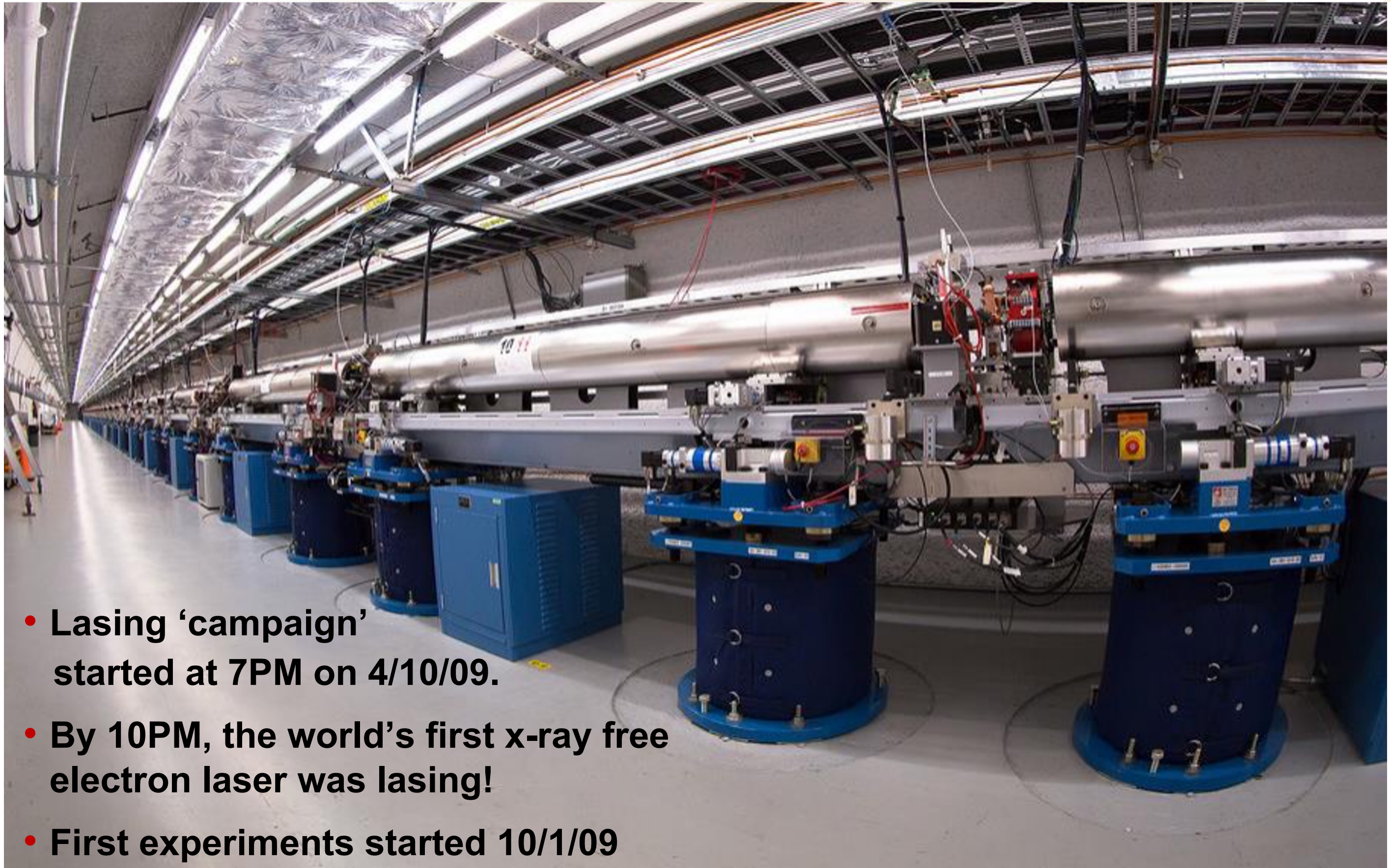


- Free relativistic electrons in bunch radiate in periodic H-field
- Amplification through electron ordering in its own radiation

X-ray pulse parameters

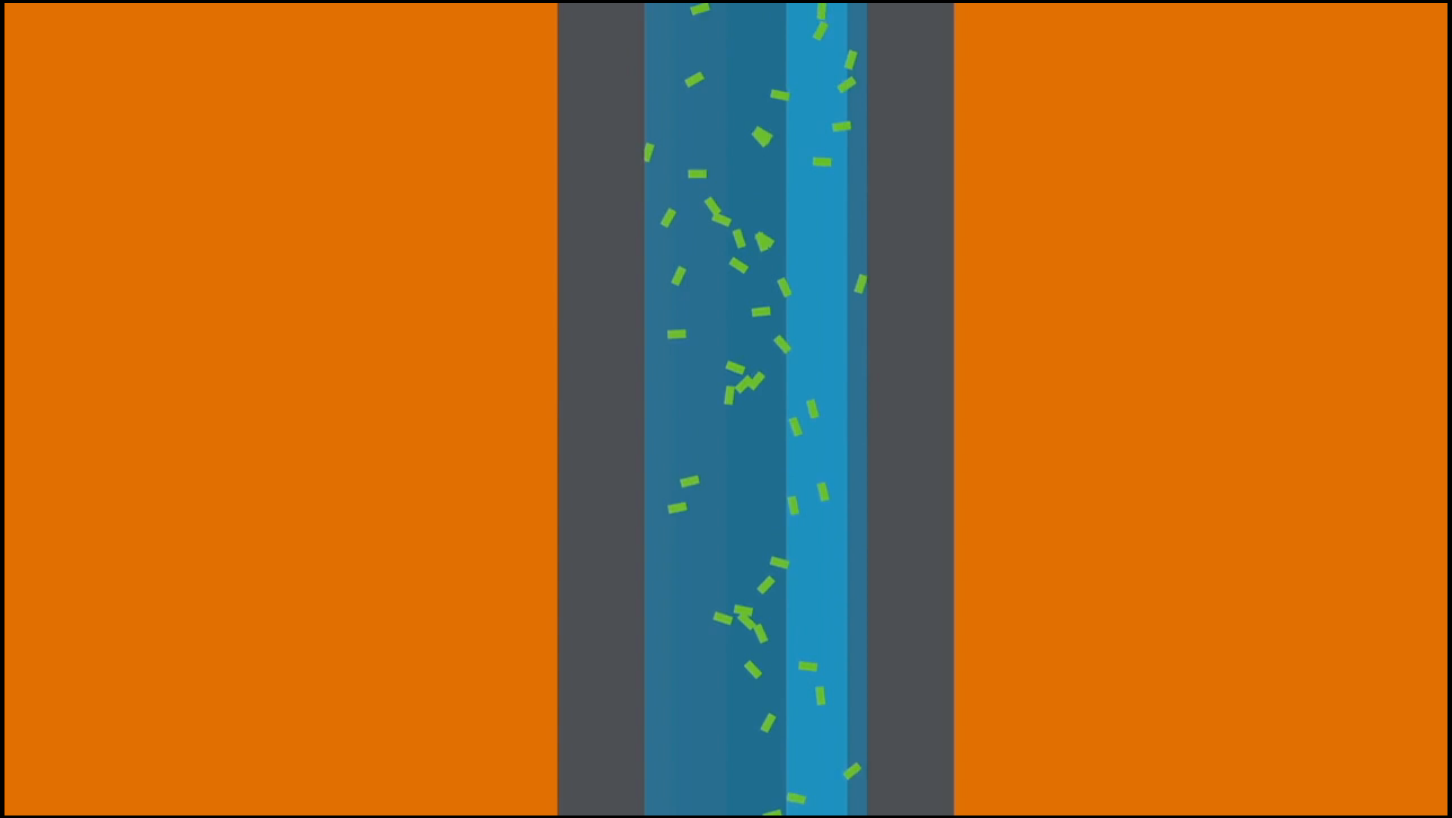
- 1-100 femtoseconds
- Tunable energy to 20 keV
- Angstrom wavelength
- 120 Hz now, 1 MHz LCLS-II

Inside View: LCLS Undulator Tunnel



- Lasing 'campaign' started at 7PM on 4/10/09.
- By 10PM, the world's first x-ray free electron laser was lasing!
- First experiments started 10/1/09

We make real-time movies of the molecules that plants use to split water



courtesy of SLAC

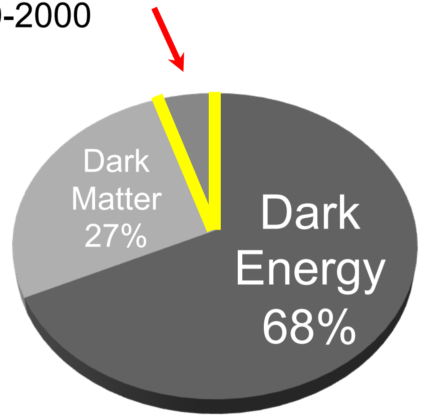
Fuller et al., *Nature Methods* (2017) doi:10.1038/nmeth.4195

So where do we go next?

SLAC

In ***Particle Physics*** the frontier is electron-positron collisions > 1 TeV

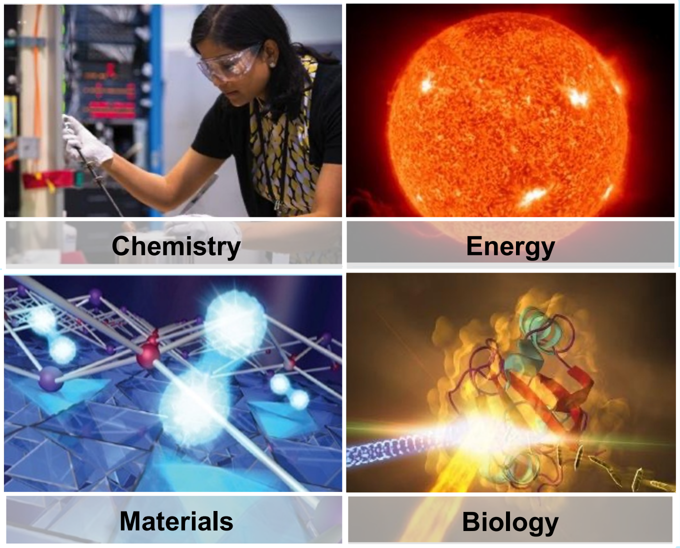
The 5% studied with particle accelerators 1960-2000



High Impact Applications **for electron & ion accelerators & RF technology**

- Medicine
- Energy & environment
- Security and defense
- Communications, radar & remote sensing

In ***X-ray Science*** the next light source will be > $1 B and the beam time will likely be oversubscribed.

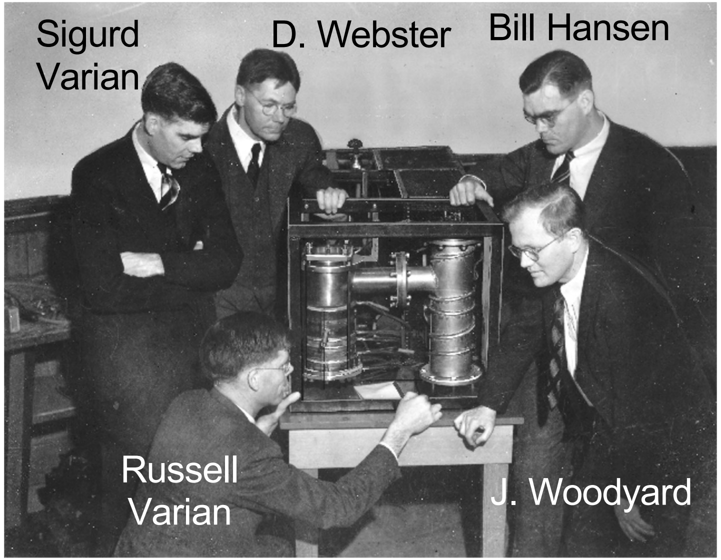


RF Accelerator Technology Got its Start With Key Technology Developments in the decades Flanking WWII

Use of RF resonant cavities for particle acceleration

First 3-foot section of MARK I electron linear accelerator at Stanford (William Hansen and three of his students) 1947.

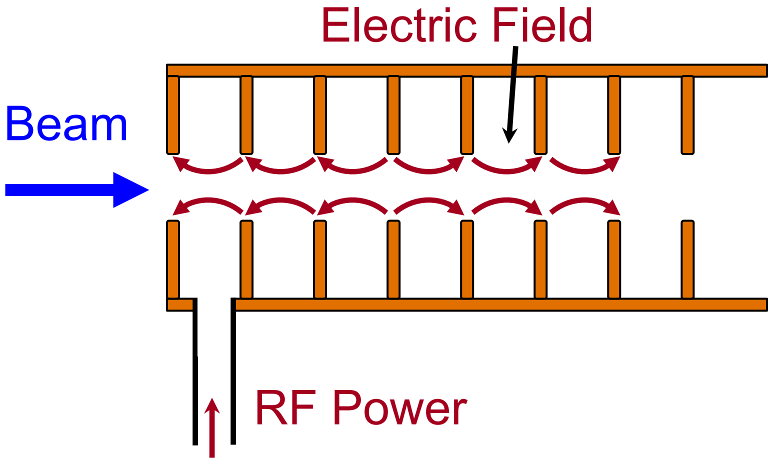
Powerful RF sources



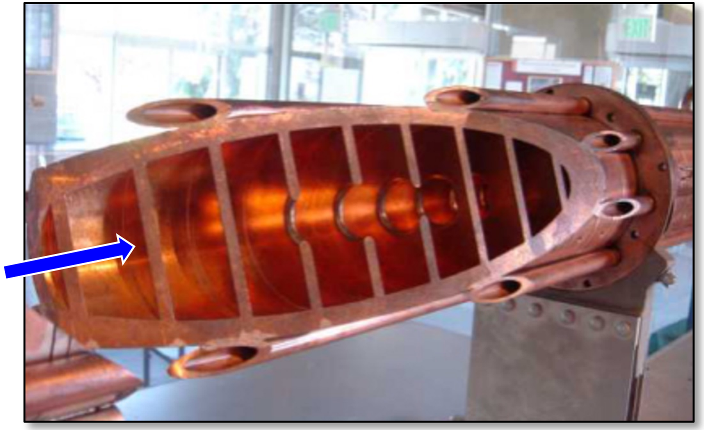
250 MHz klystron used for the U.S. Army blind landing system before World War II, Stanford University, 1939.

How an Radiofrequency Linear Accelerator Works

Disk Loaded Waveguide Structure

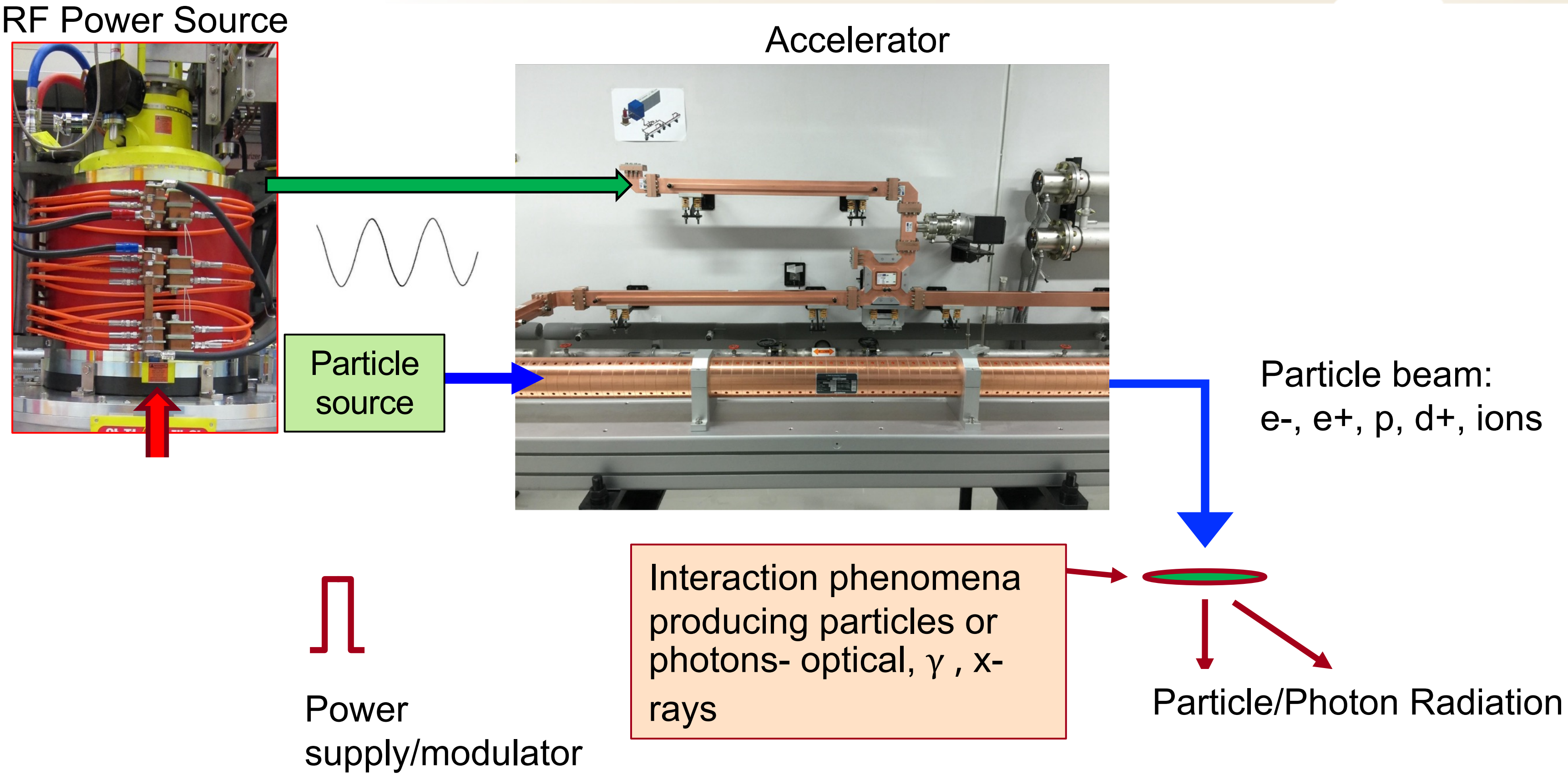


Section of the SLAC (2 Mile) accelerator structure - 2.856 GHz



Typical gradients ~ 15-20 MeV/m

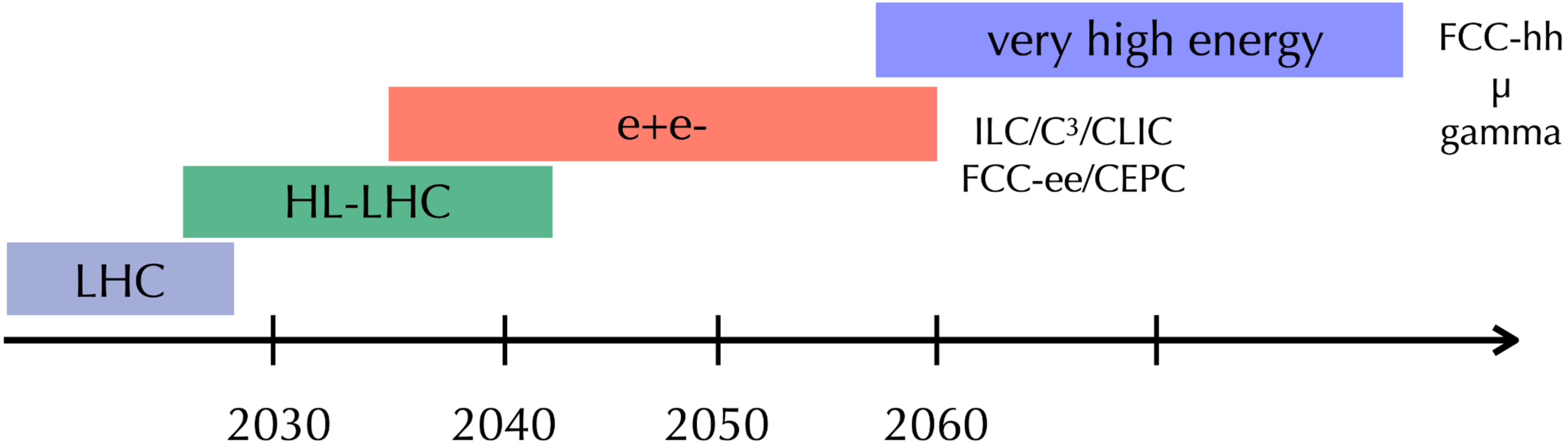
Accelerator Systems for Making Energetic Particles and Radiation



Outline

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

What's Next for the Energy Frontier?



Wish list beyond HL-LHC:

1. Establish Yukawa couplings to light flavor ⟹ needs precision
2. Establish self-coupling ⟹ needs high energy

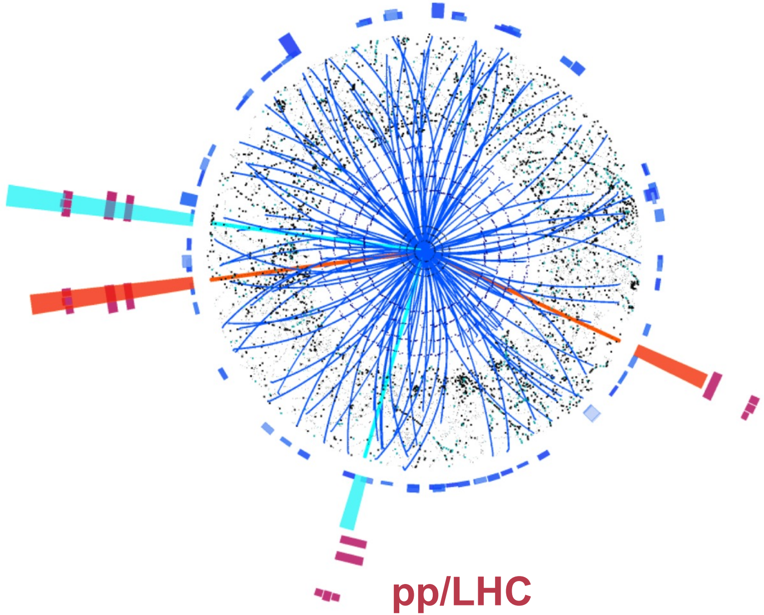
For the next e+e- Linear Collider

1. 5X the Beam Energy
2. 1000X the Luminosity (Effectively Beam Power Density)

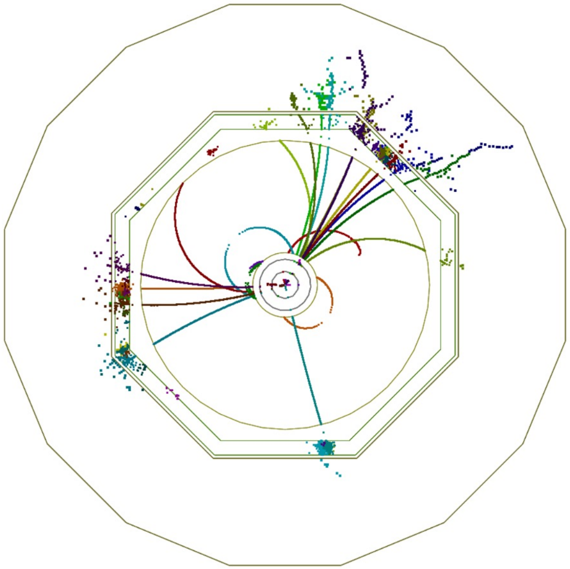
Why e^+e^-?

Initial state well defined & polarization $\Longrightarrow$ High-precision measurements

Higgs bosons appear in 1 in 100 events $\Longrightarrow$ Clean environment and trigger-less readout



pp/LHC



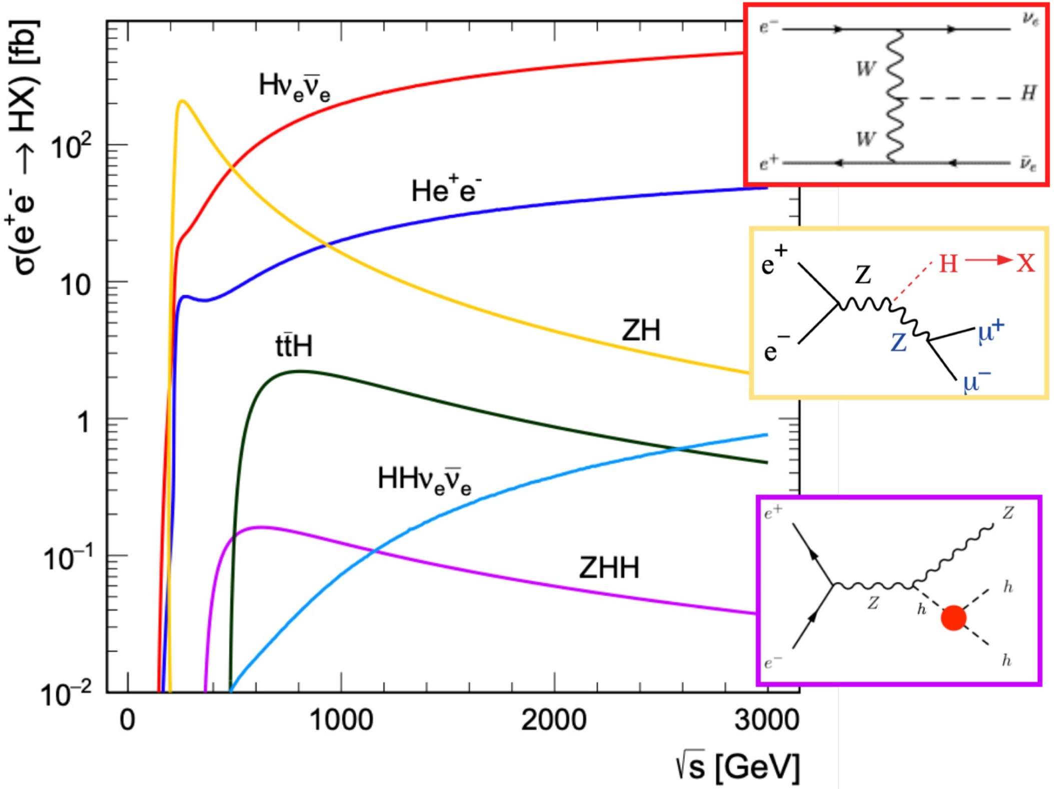
e^+e^-

Higgs Production at e^+e^-

ZH is dominant at **250 GeV**

Above **500 GeV**

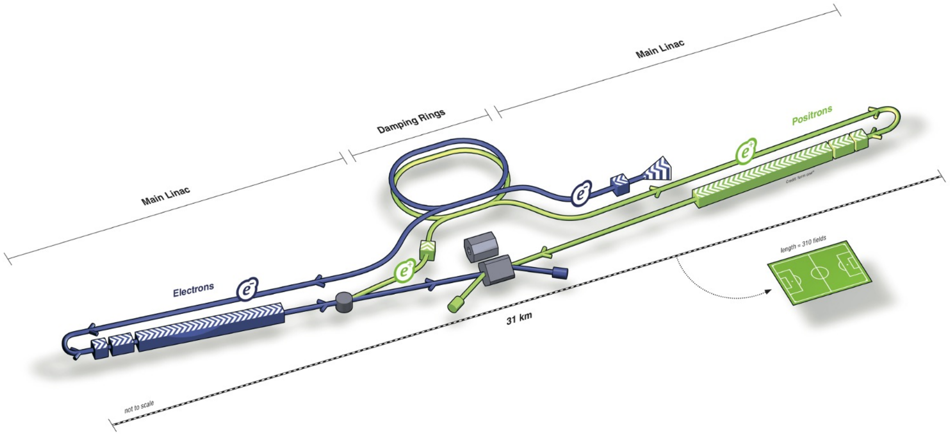
- Hvv dominates
- ttH opens up
- HH production accessible with ZHH



Linear vs. Circular

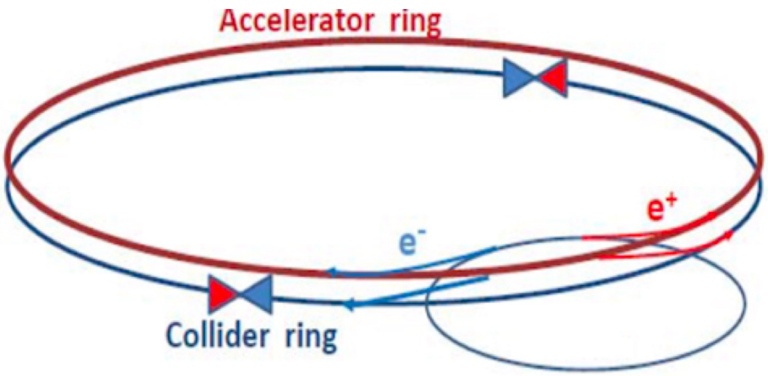
Linear e^+e^- colliders: ILC, C^3, CLIC

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

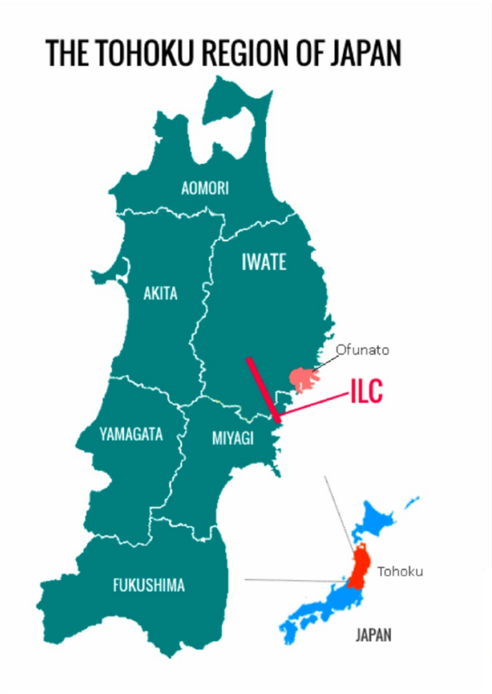


Circular e^+e^- colliders: FCC-ee, CEPC

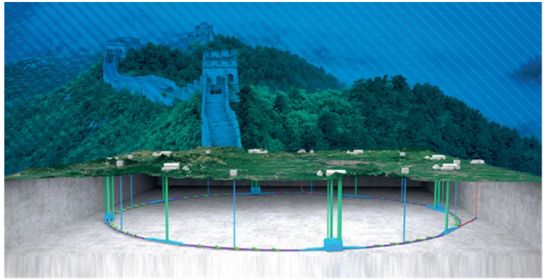
- Highest luminosity collider at Z/WW/ZH
- limited by synchrotron radiation above 350 – 400 GeV
- Beam continues to circulate after collision



Various Proposals

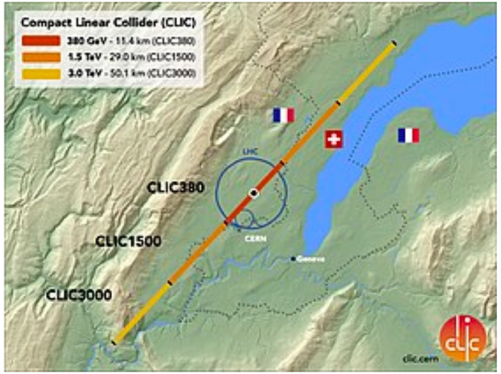


ILC
250/500 GeV

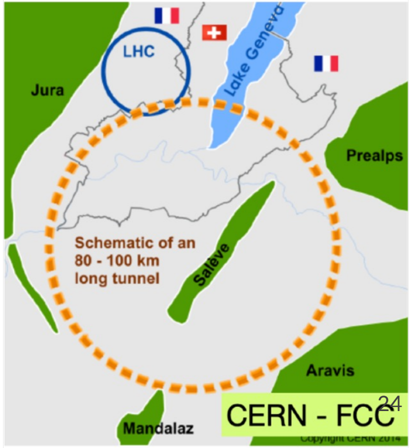


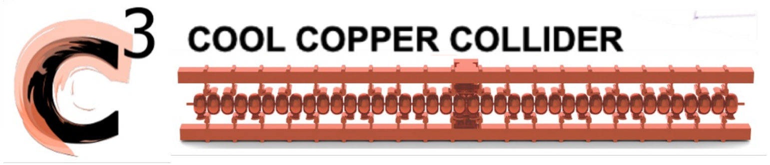
CEPC
240 GeV

CLIC 380/1000/3000 GeV



FCC-ee
240/365 GeV





250/550 GeV
... > TeV

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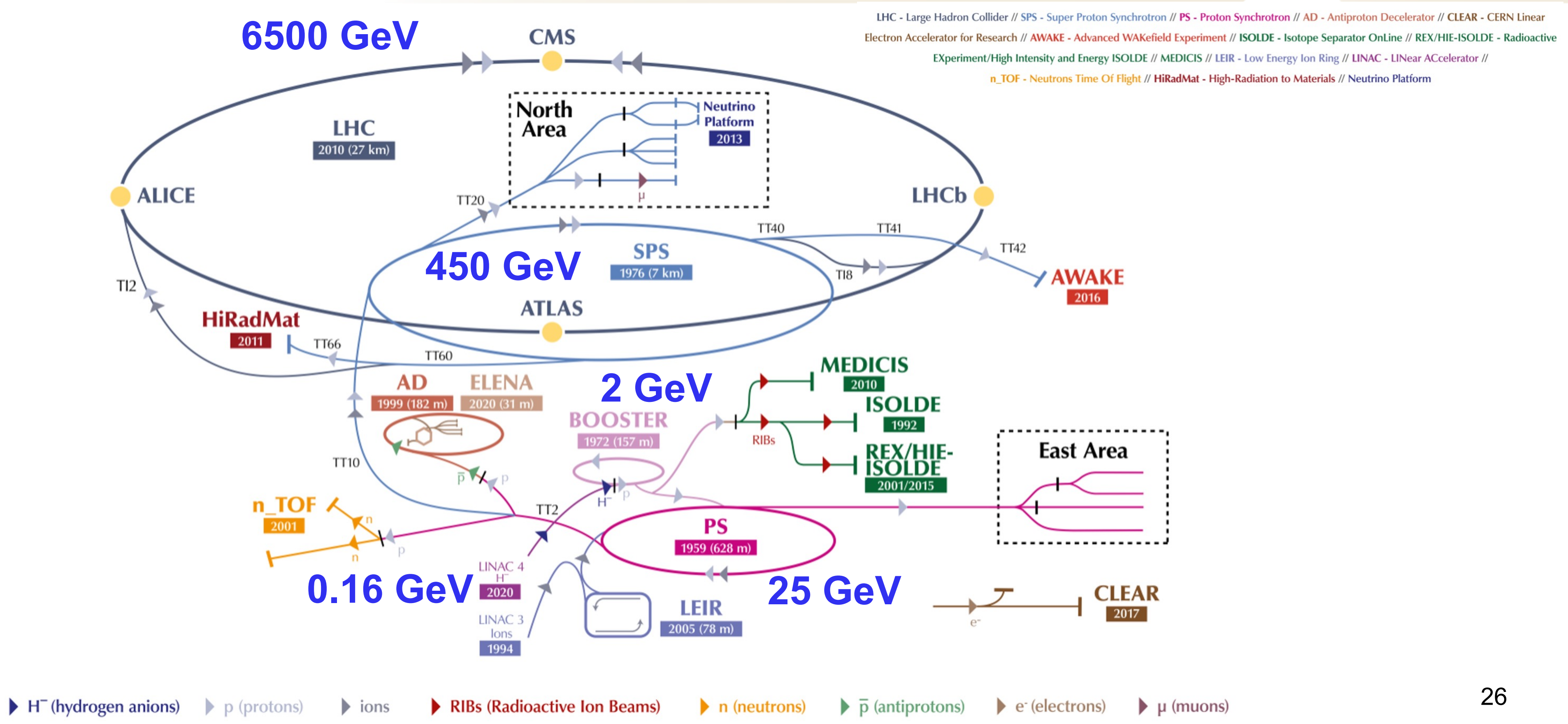
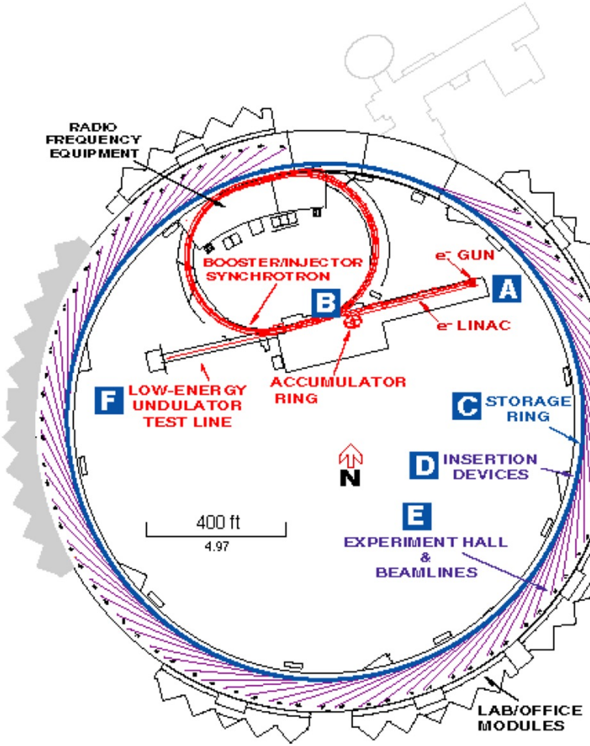
CERN Accelerator Complex

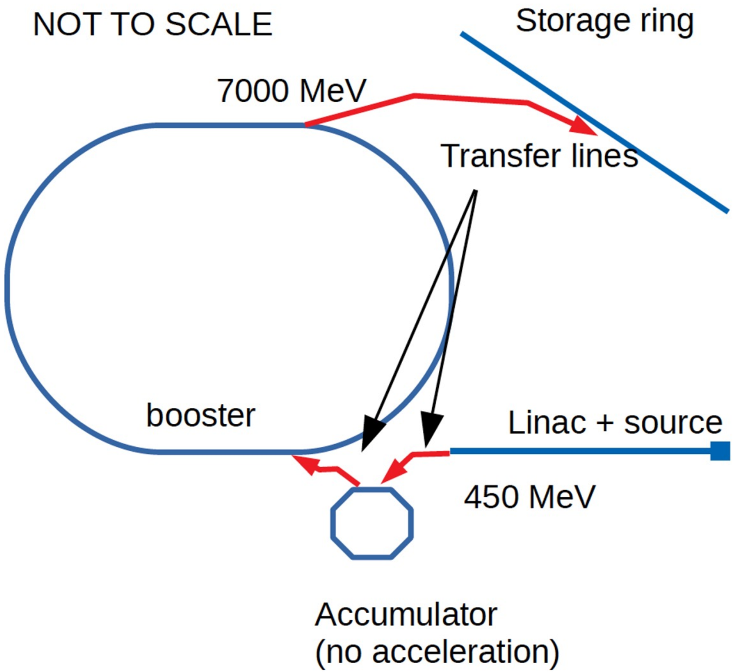


Advanced Photon Source

- X-ray synchrotron light sources contain many of the key components of accelerator facilities

Schematic View of the Advanced Photon Source

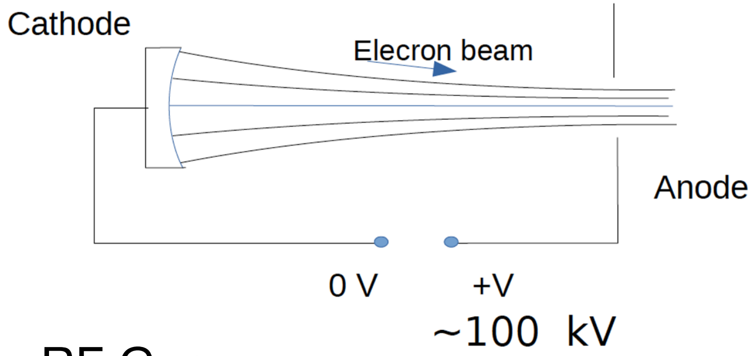




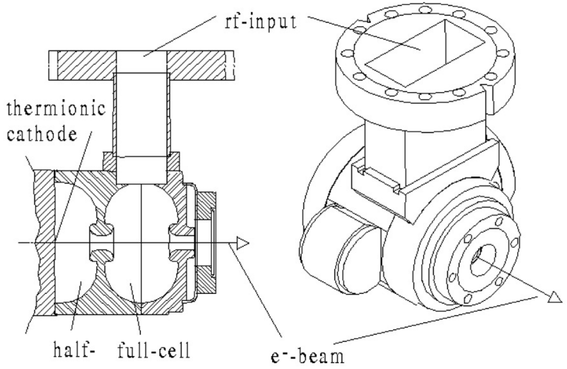
Particle (Electron) Sources

- Electrons emitted by providing enough free energy to overcome binding energy
- Thermionic, field and/or photo emission
- Need electric fields to accelerate particles away from the surface

DC Gun



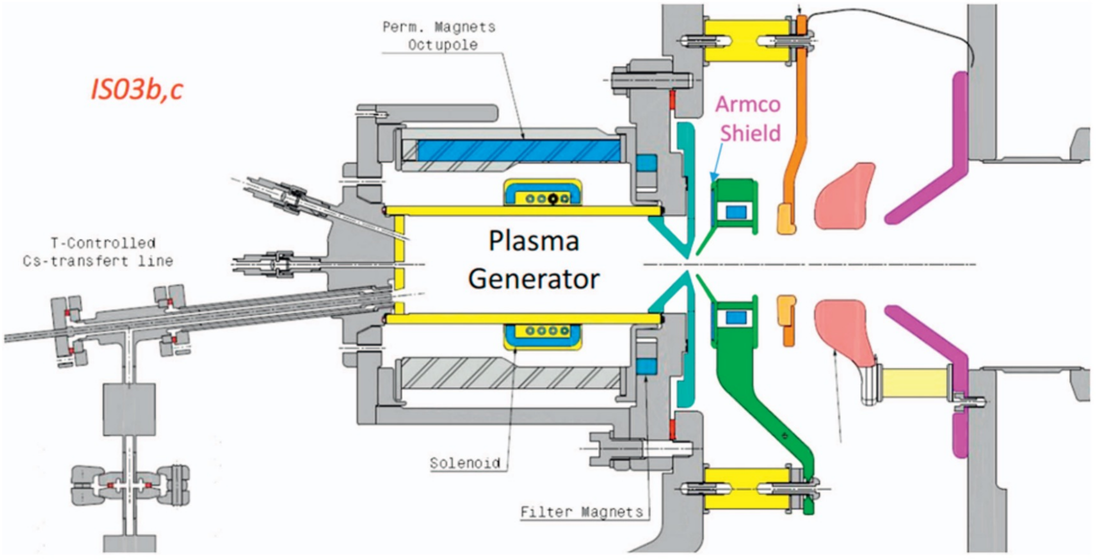
RF Gun



Particle (Ion) Sources

- Ionize gas and accelerate
- Set desired ionization by stripping or adding electrons
- Select ionization with magnets

Schematic of CERN's LINAC4 source



Real Particle Sources

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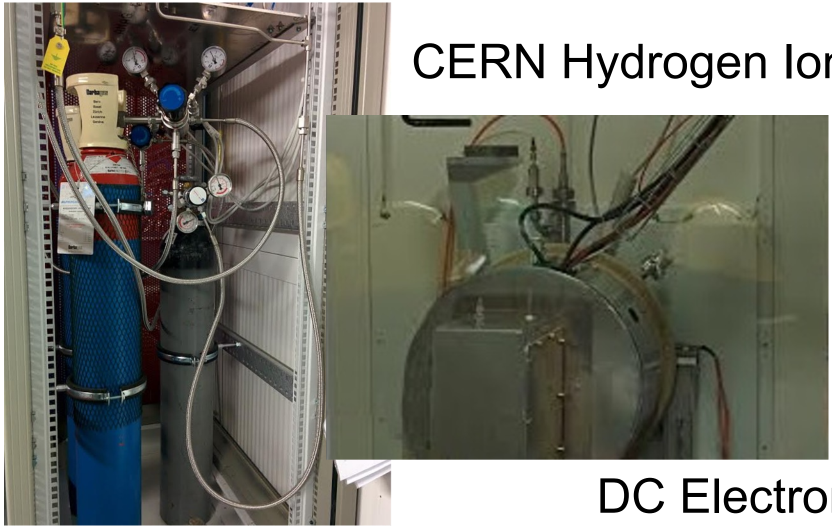
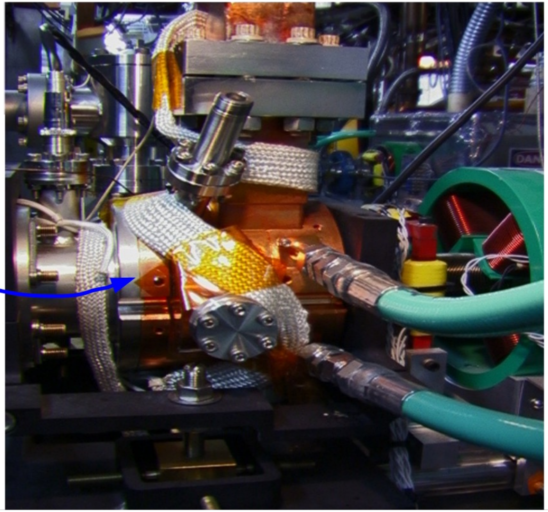
CERN Hydrogen Ion Source



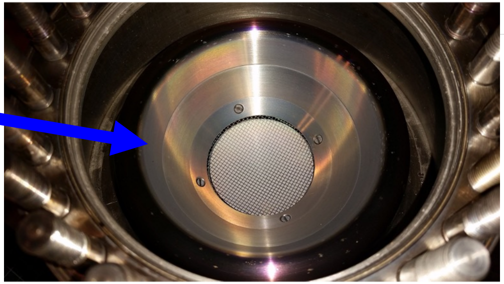
RF Electron Gun



cathode somewhere inside

cooling hose that you see on most accelerator components

DC Electron Gun

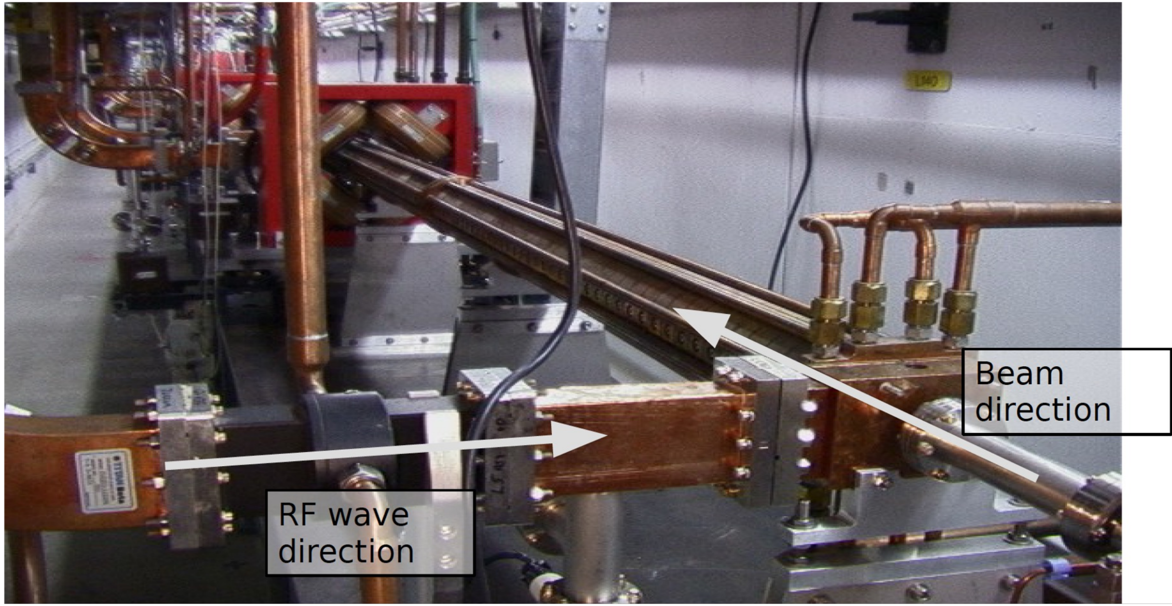


Emitter heated to 1000 ^{o}C

RF Linear Accelerator Increases Beam Energy

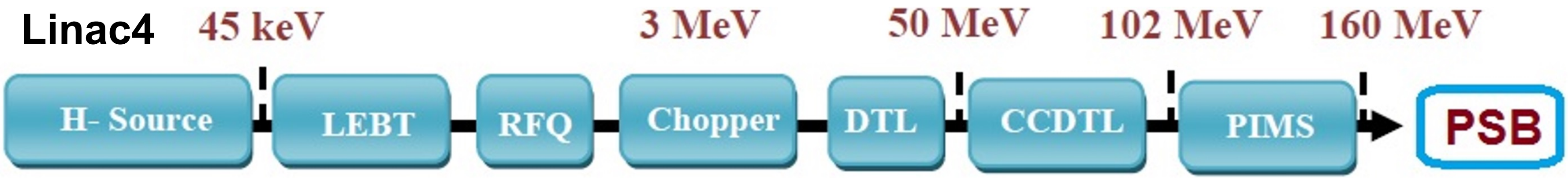
- Electromagnetic wave accelerates particles to higher energy
- Linear accelerator is common for injection into a circular machine
- Higher beam quality; used to bunch, focus and compress beam

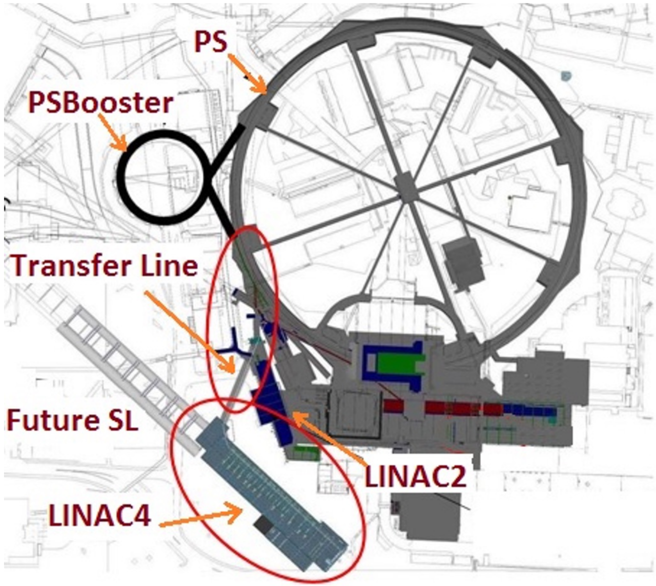
Electrons at APS

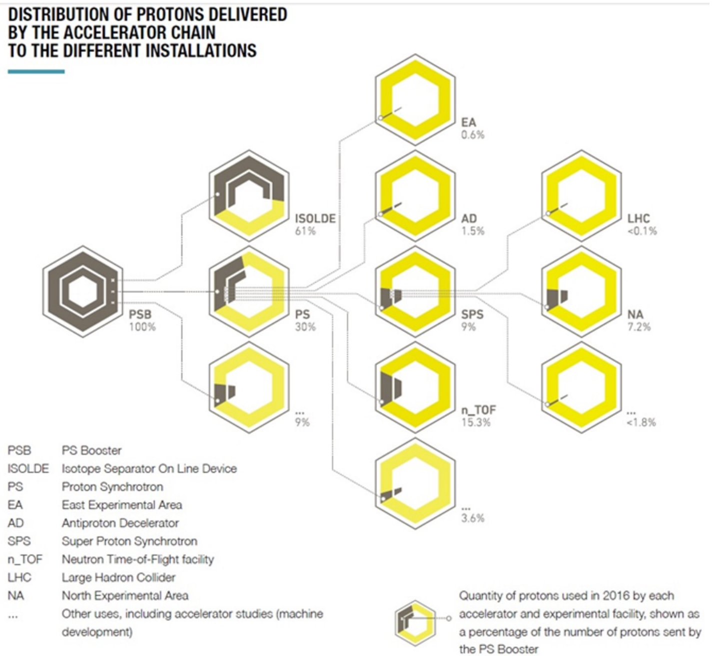


RF Linear Accelerator Increases Beam Energy @ CERN

Linac4

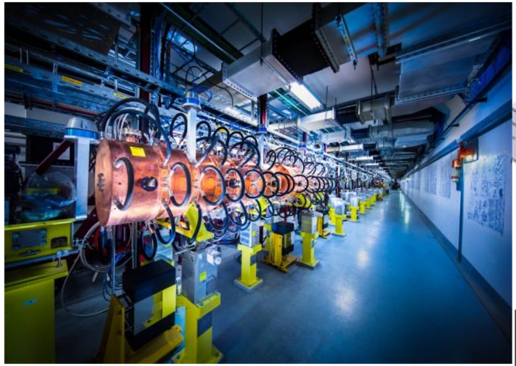


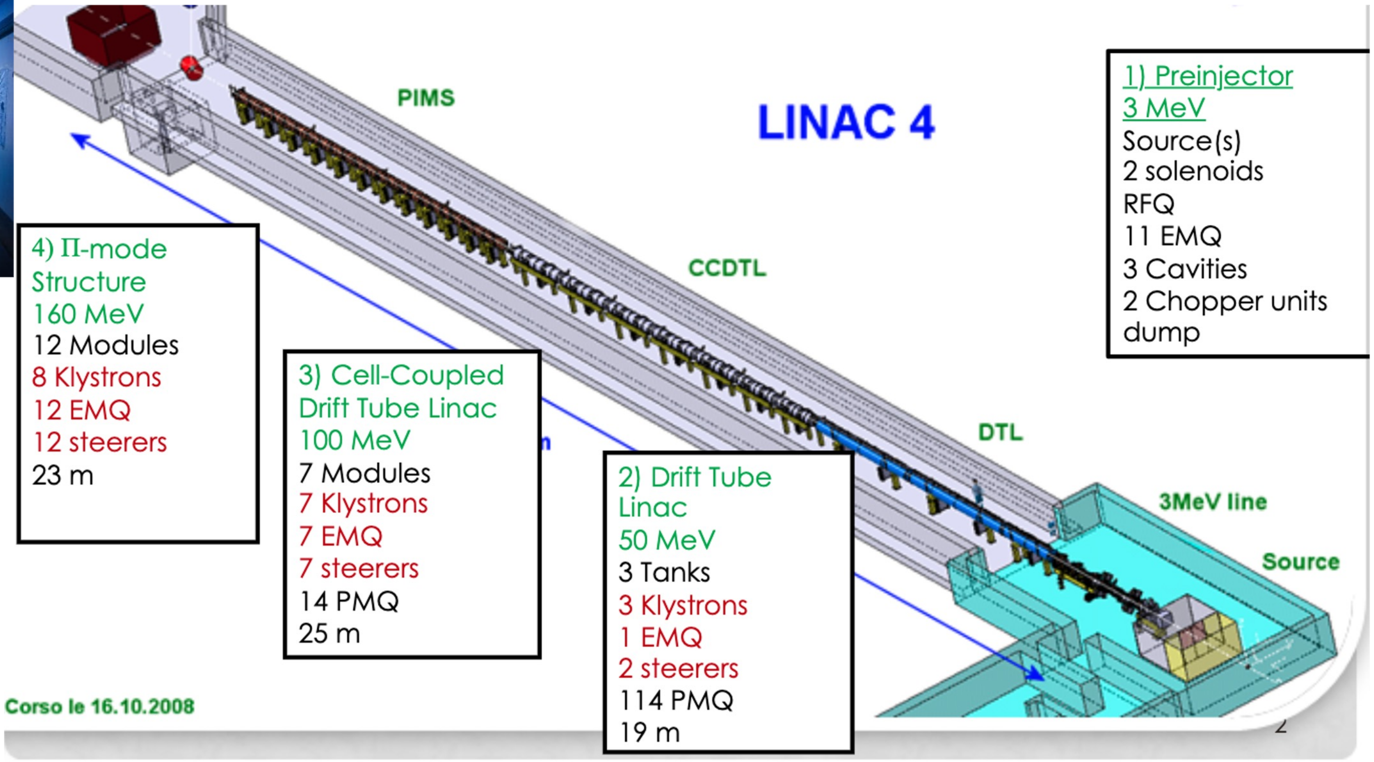




The Proton Source: Linear Accelerator 4 (Linac4)

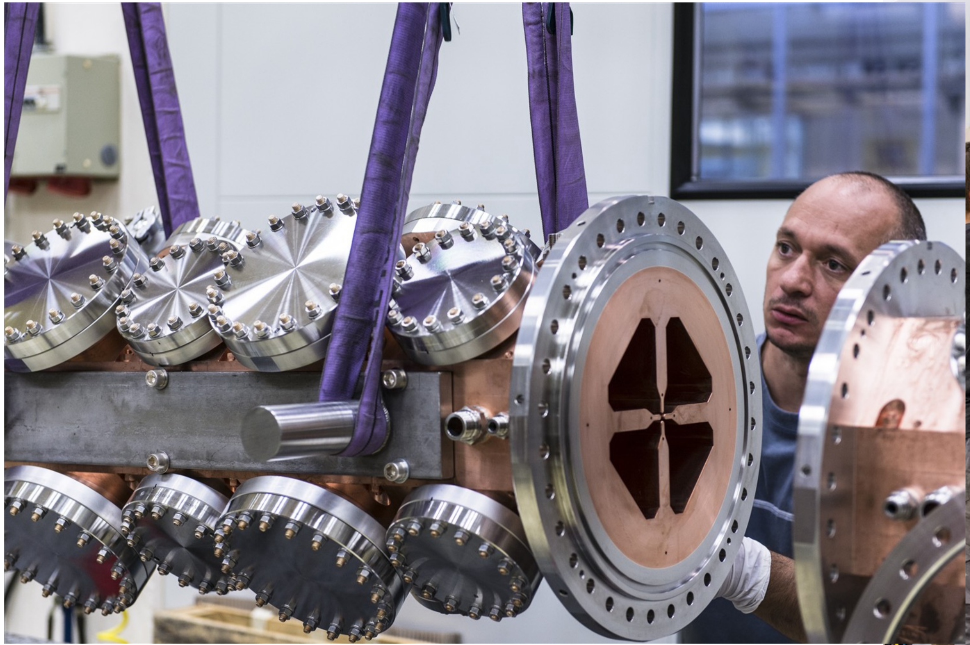
SLAC



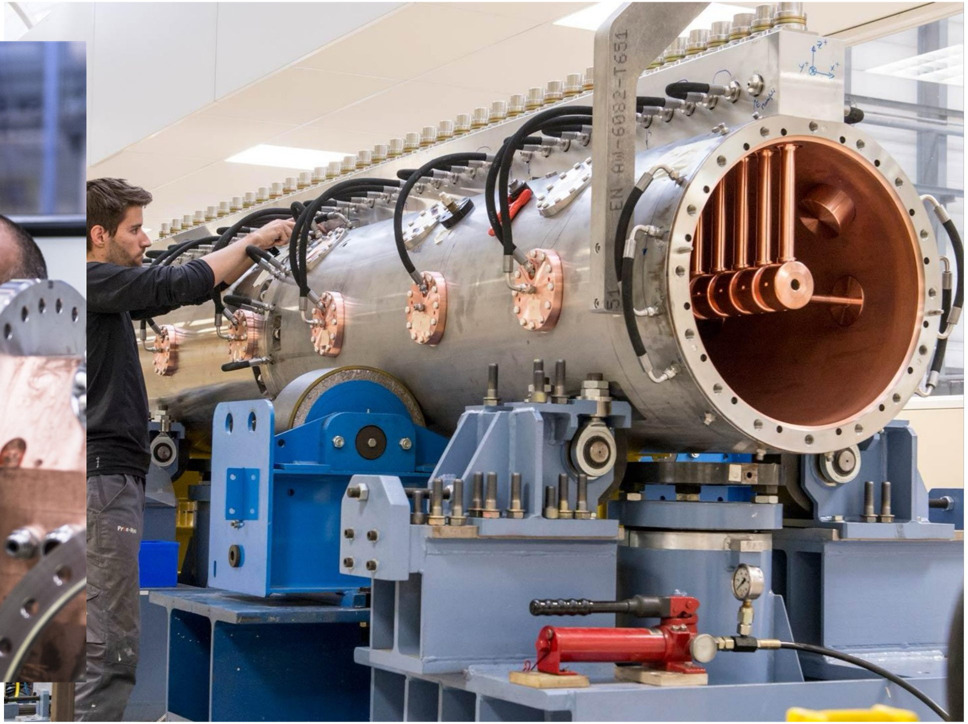


RF Cavities in Linac4

Linac4 Radio Frequency Quadrupole

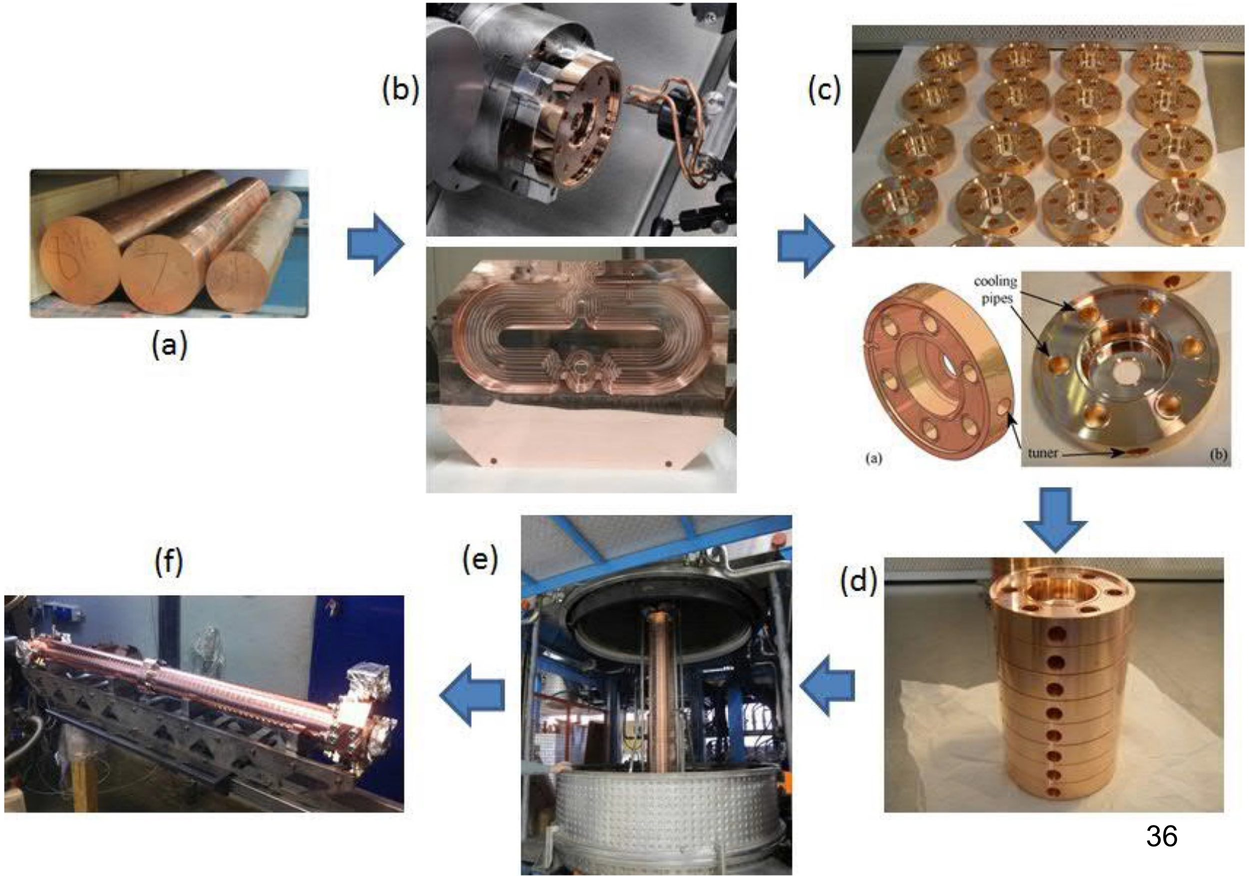


Linac4 Drift Tube Linac



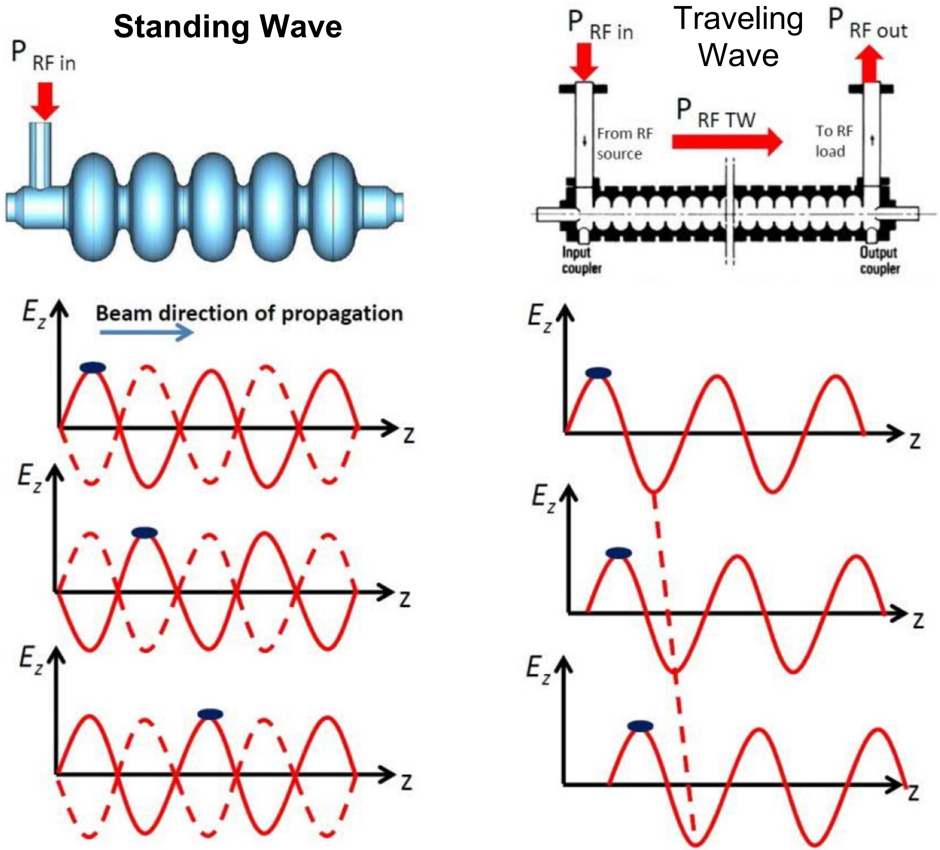
Fabrication of RF Accelerators

(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.

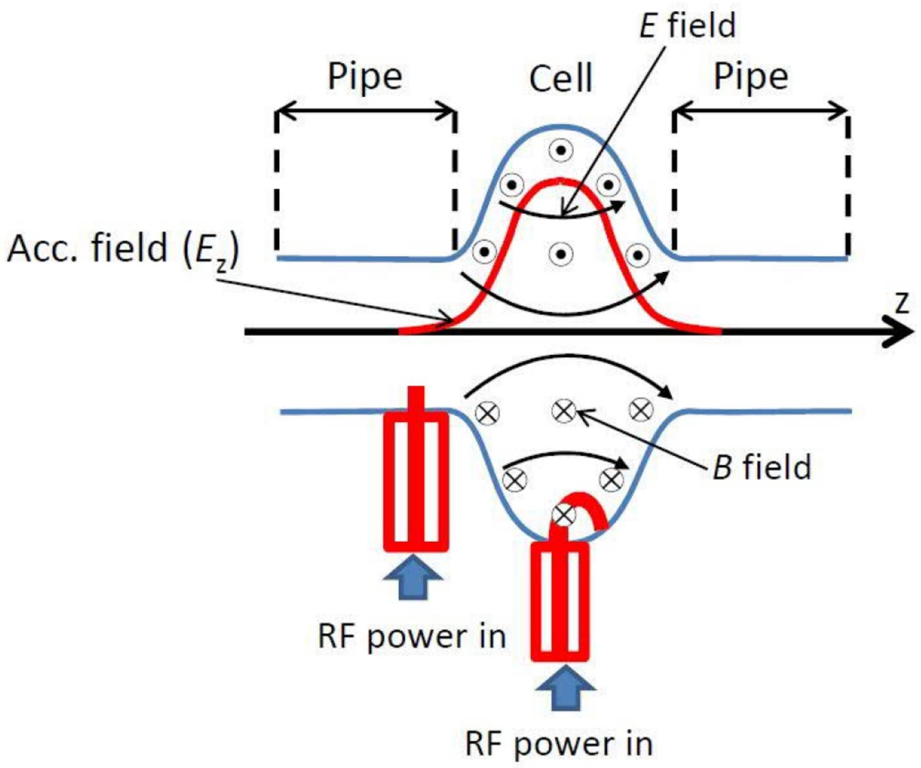


Electromagnetic Fields Used to Accelerate Particles

- 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



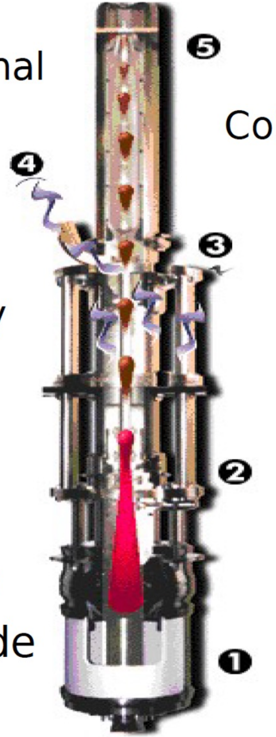
$$E_z(z,t) = E_{RF}(z)\cos\left(\underbrace{2\pi f_{RF}}_{\omega_{RF}} t + \varphi\right) = \mathrm{Real}\left[\tilde{E}_z(z)\, e^{j\omega_{RF} t}\right]$$

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

RF Sources Power the Accelerator

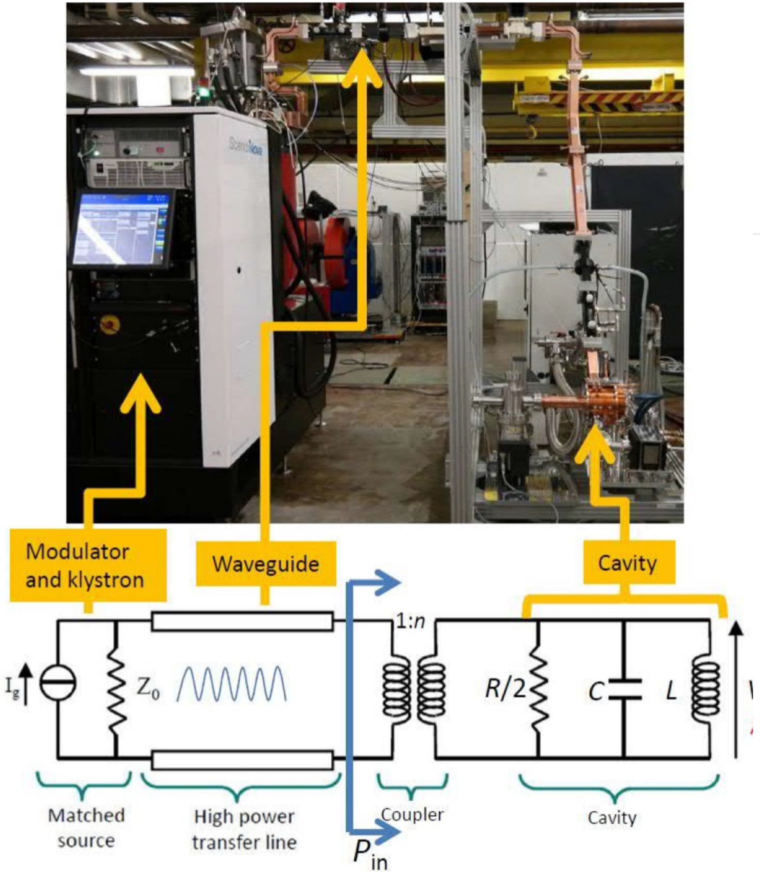
SLAC

RF Source (Klystron)

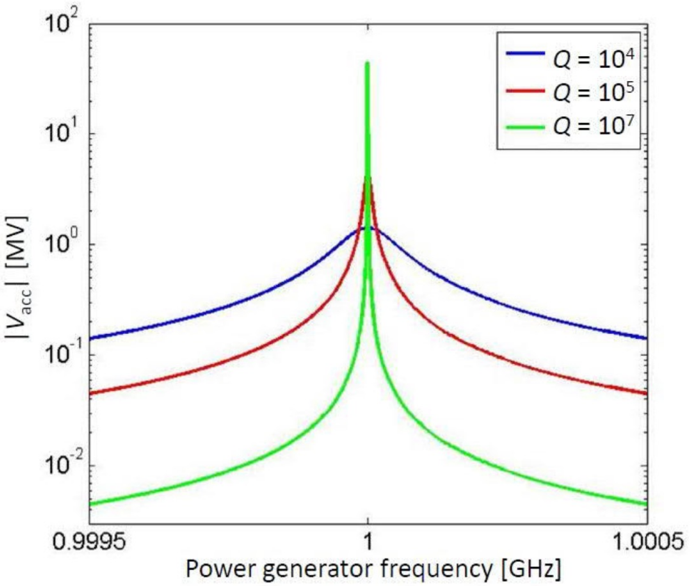


400 MHz, 500 kW LHC Klystron

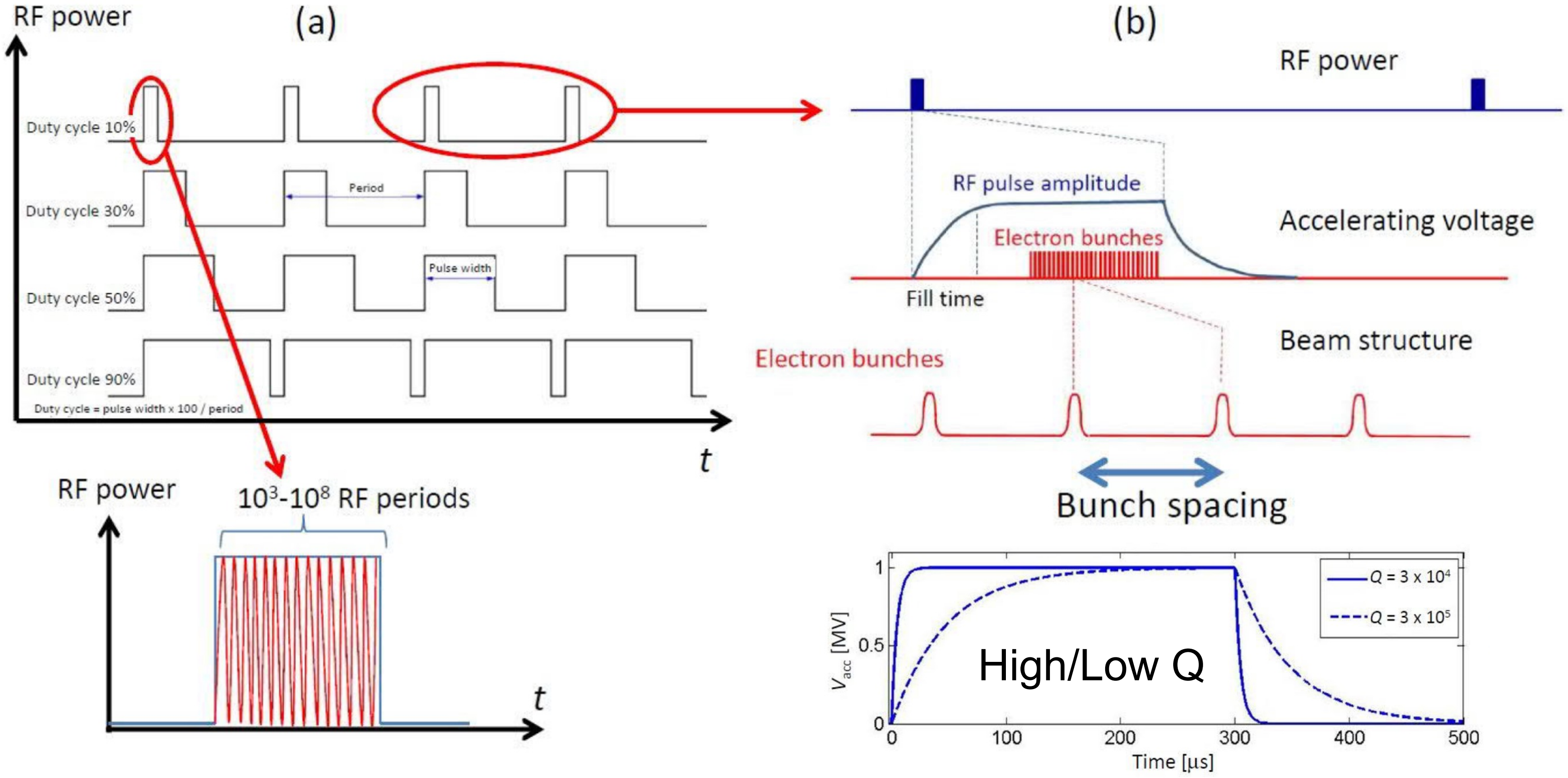
Circuit Model for Powering Accelerators



- High quality factor increases energy gain for fixed power

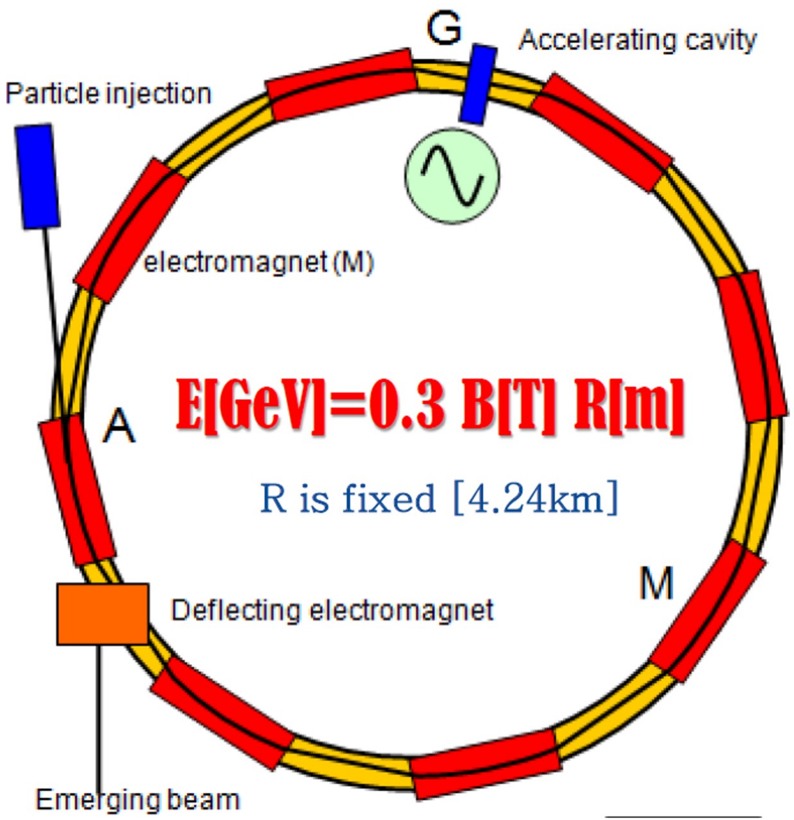


RF and Beam Pulse Structure



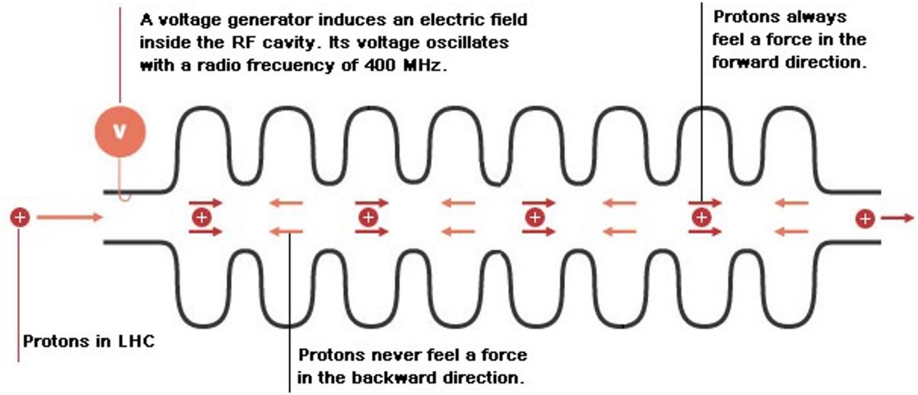
LHC Synchrotron

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

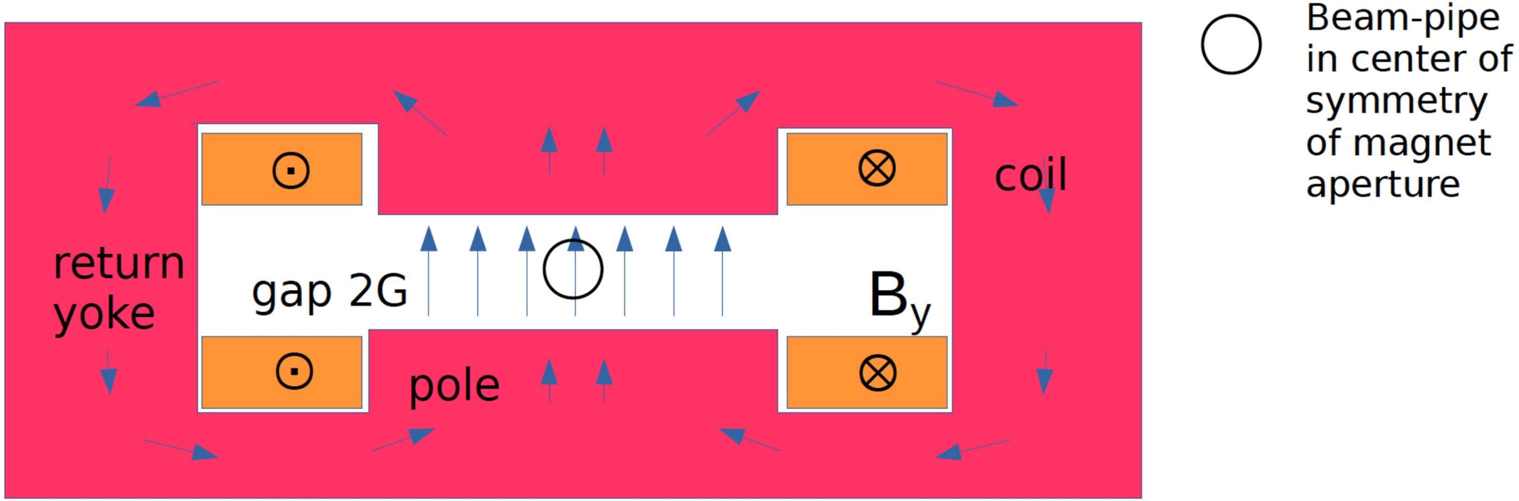


LHC Cryomodule

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.



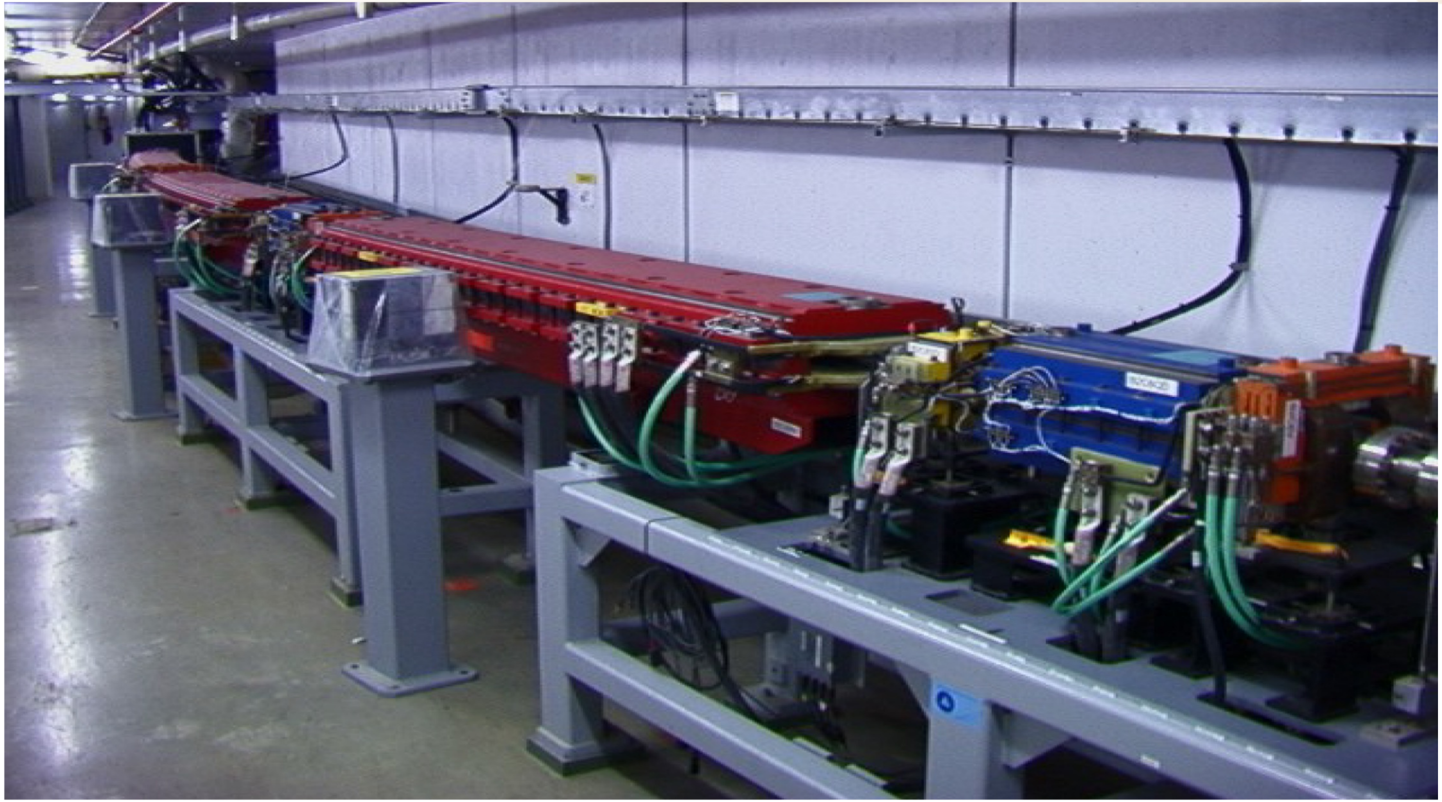
Magnets Guide and Transport the Beam



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

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

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

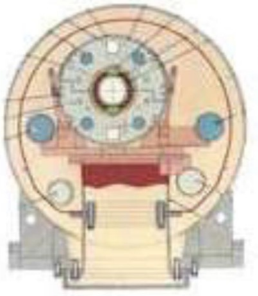
5.3T

HERA,
9 m, 75 mm
416 dipoles

NbTi cable
cold iron
Al collar

3.5T

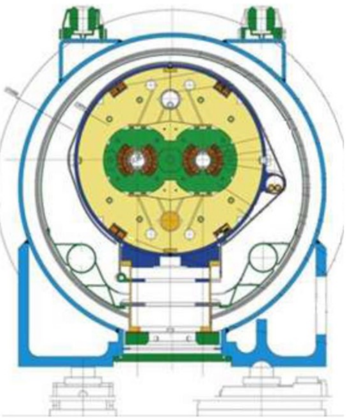
RHIC,
9 m, 80 mm
264 dipoles



NbTi cable
simple &
cheap

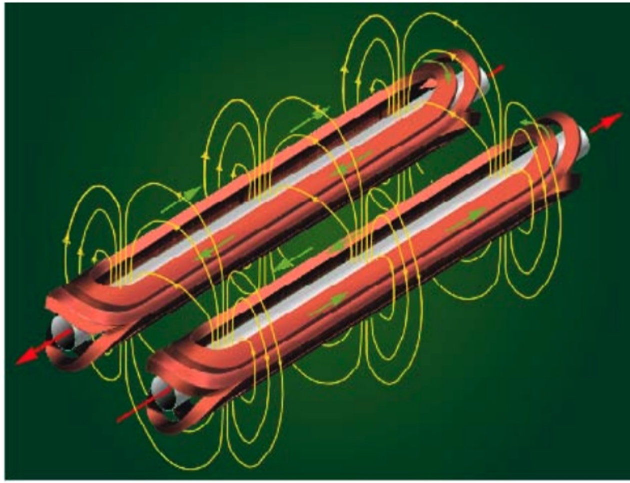
8.3T

LHC,
15 m, 56 mm
1276 dipoles



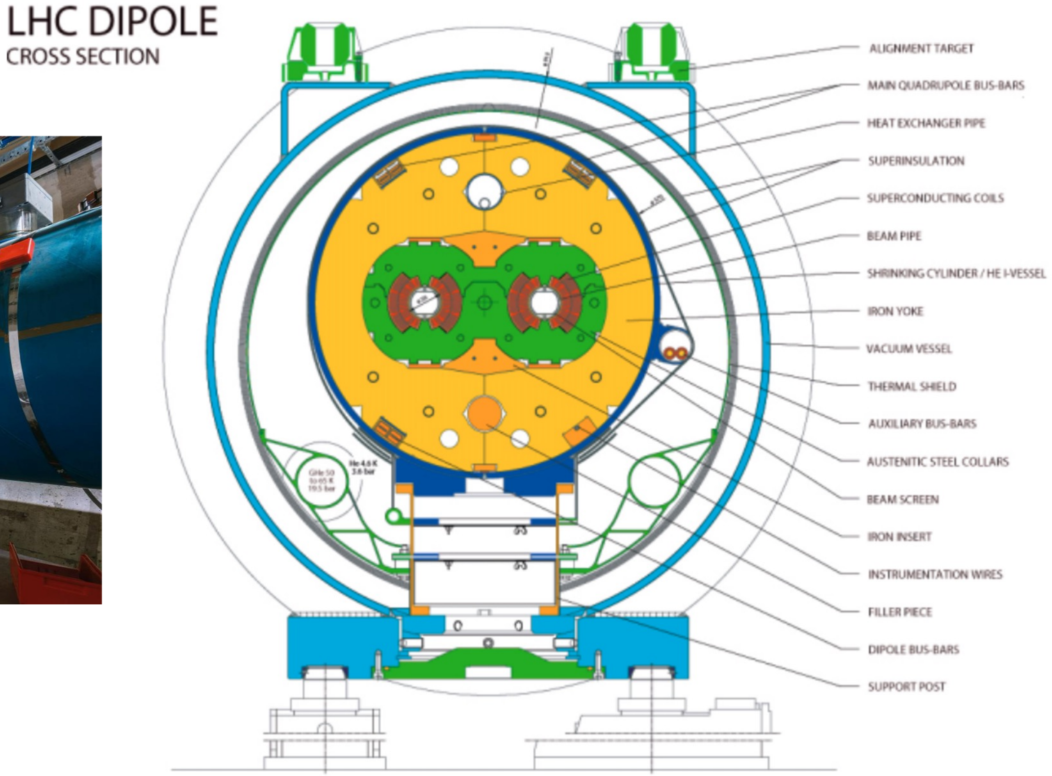
NbTi cable
2K He
two bores

Dipole Field Produced by SC Tape



LHC Superconducting Magnets

LHC Dipole in Tunnel

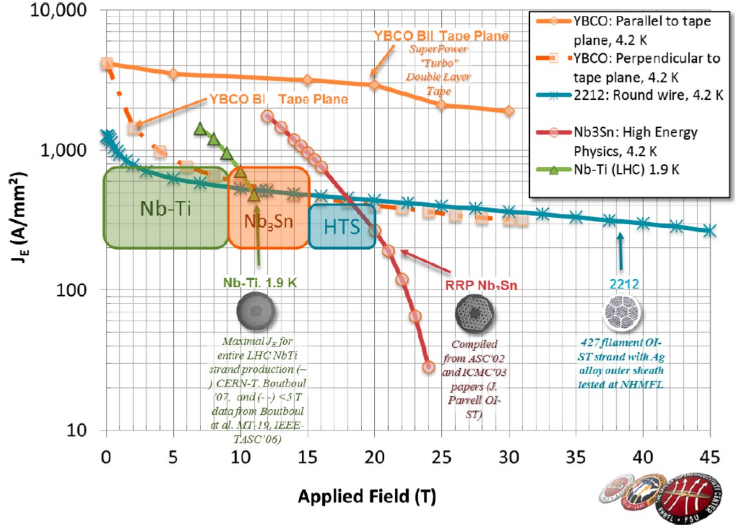


CERN AC/DI/MM — 06-2001

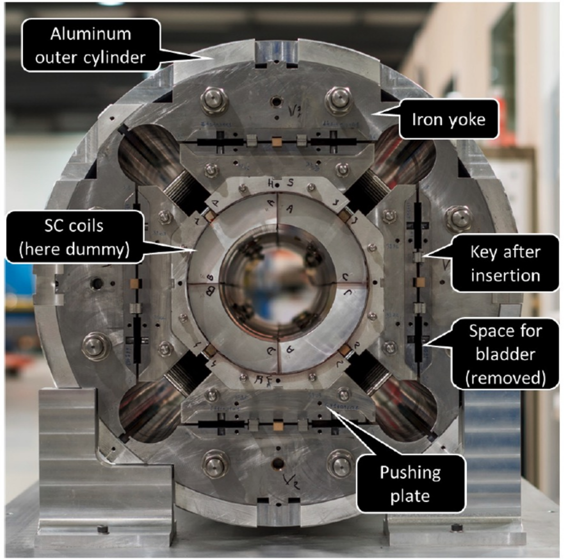
Path Forward for Superconducting Magnets

- 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



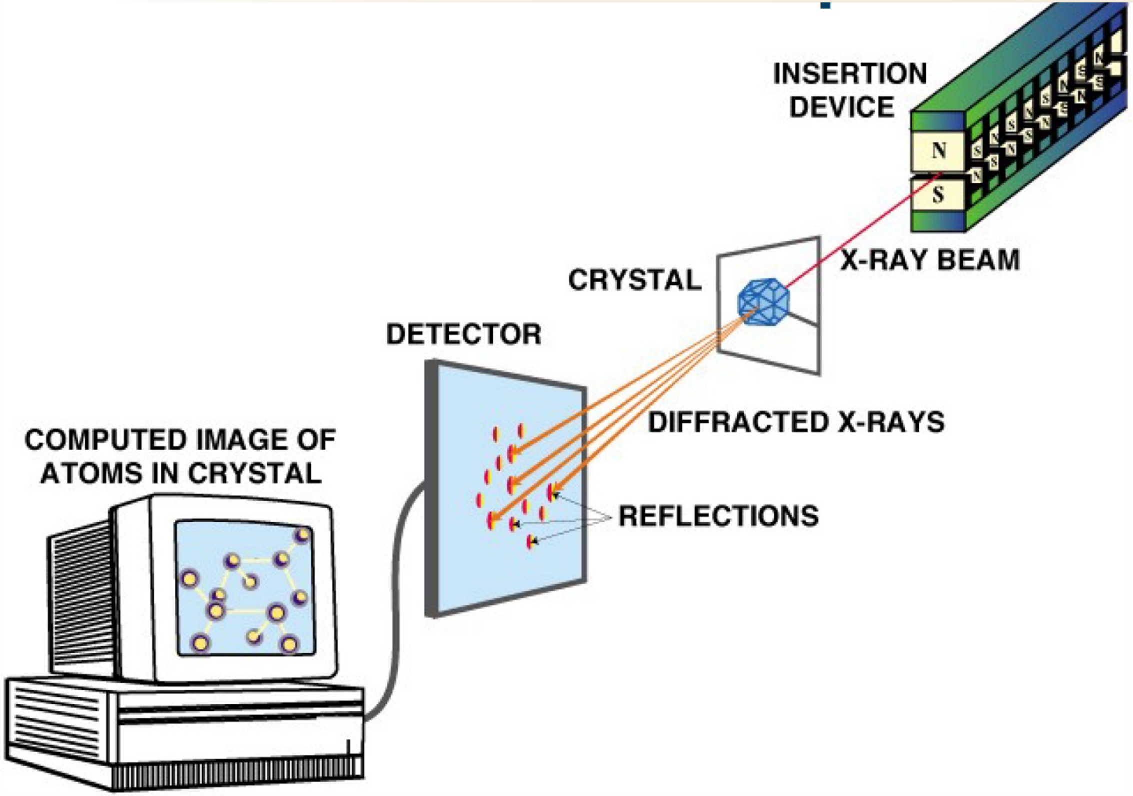
HL-LHC Nb3Sn IT Quad



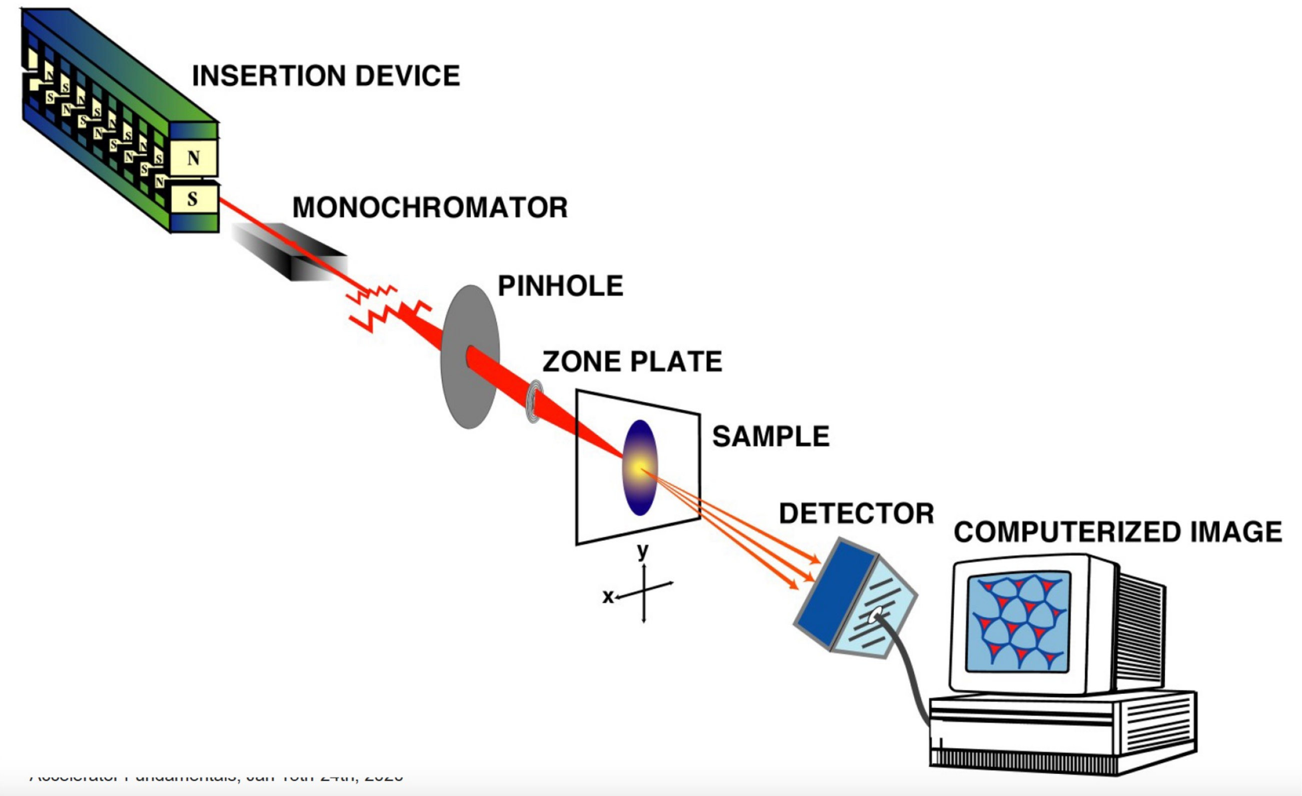
Existing quads
- 70 mm aperture
- 200 T/m gradient

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

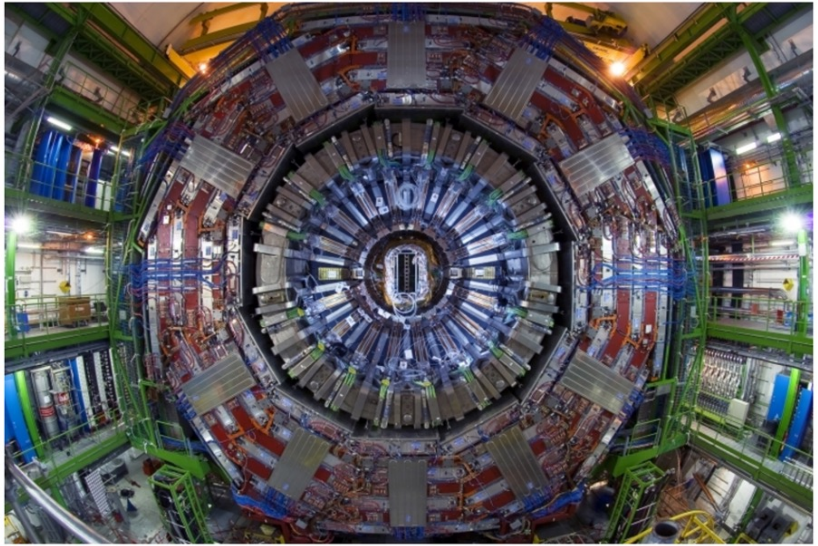


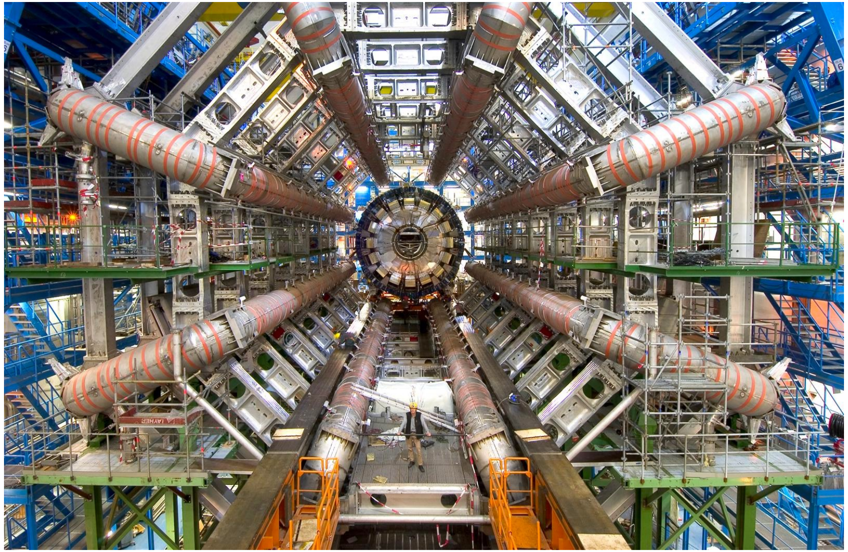
Applications Side – X-ray Imaging



Application Side: Particle Physics

CMS & ATLAS at CERN





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
- Close interaction between users and accelerator physicists and engineers leads to the best outcomes

Questions?

Questions?

Appendix

Relativity and Units

Useful Terms:

Caution: Beta will also be used for beta function

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

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

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

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

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

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

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

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

Units:

Will use SI units, except

Energy: eV (keV, MeV, etc) [1 eV= $1.6\text{x}10^{-19}$J]

Mass: eV/c^2 [proton = $1.67\text{x}10^{-27}$kg = 938 MeV/c^2]

Momentum: eV/c [proton @ β=.9 = 1.94 GeV/c]

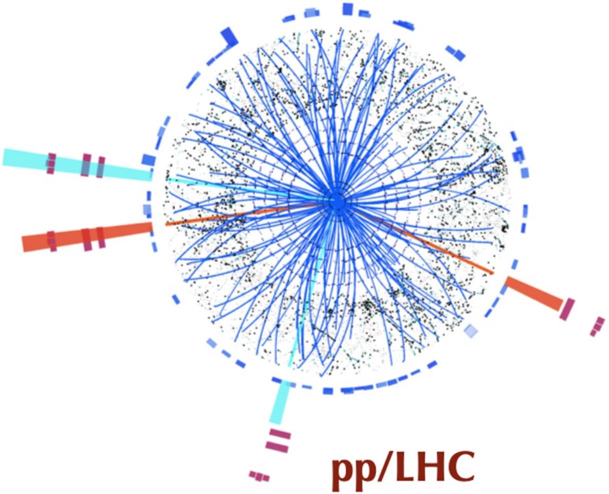
Protons vs. Electrons

Protons are made of quarks and gluons

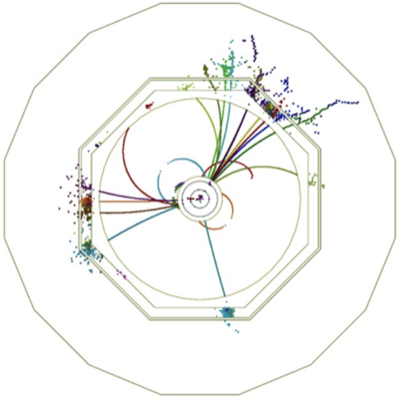
- Interaction takes place between these constituents
- Only a small fraction of energy available, not well-defined
- Rest of particle fragments

Electrons are fundamental point-like particles

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



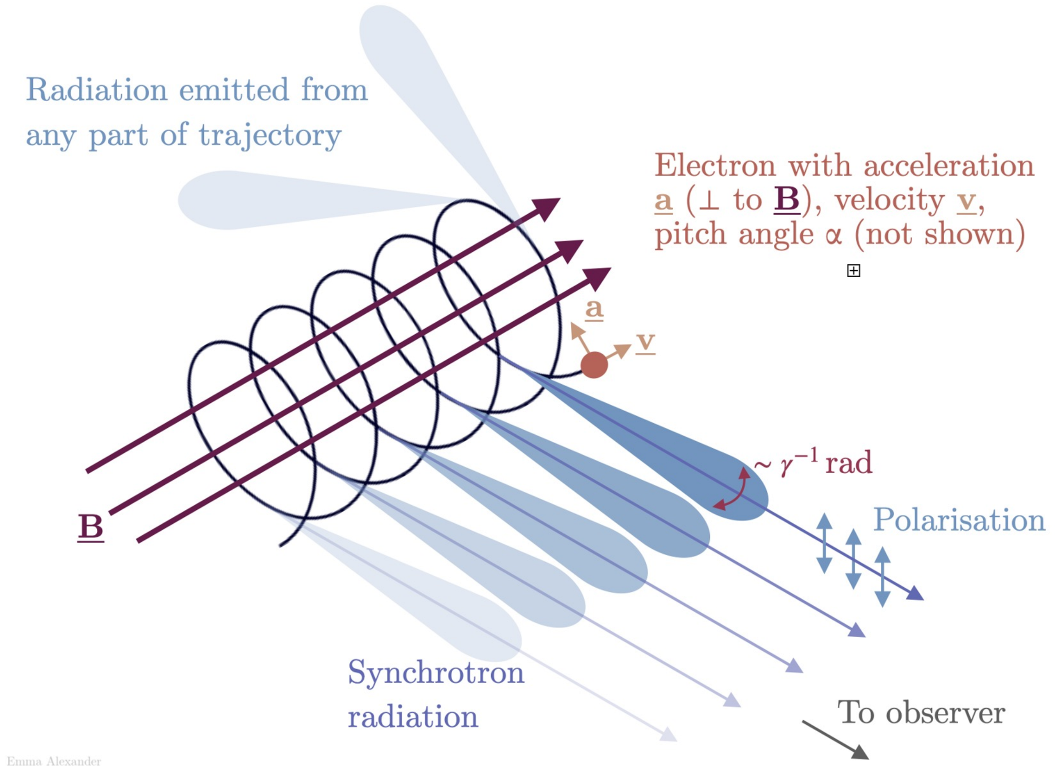
pp/LHC



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

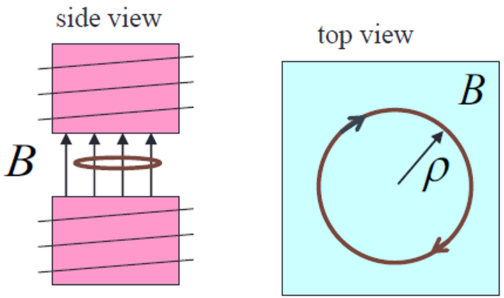
Understanding Beam Motion: Beam "Rigidity"

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

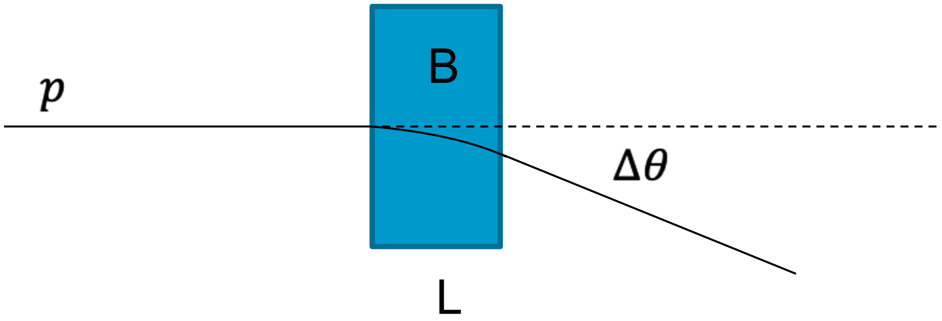
- Compare CERN Linac4 (K=160 MeV) to LHC (K=7000 GeV)

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

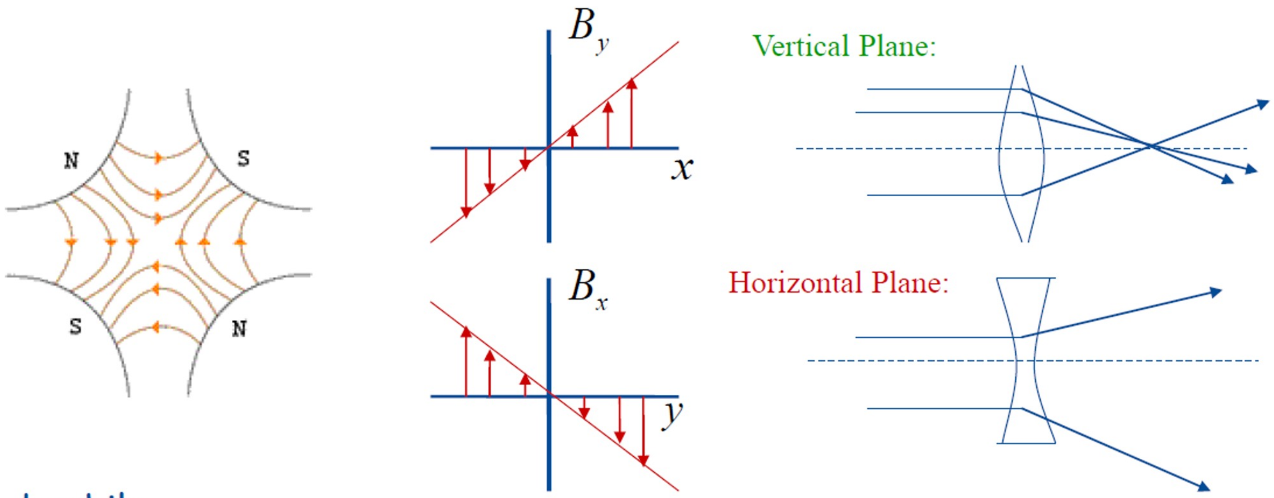


$$p_\perp = qvBt = qvB\,L/v = qBL$$

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

Focusing the Proton Beam

- Transverse field with a gradient provides focusing/defocusing



Luckily…

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

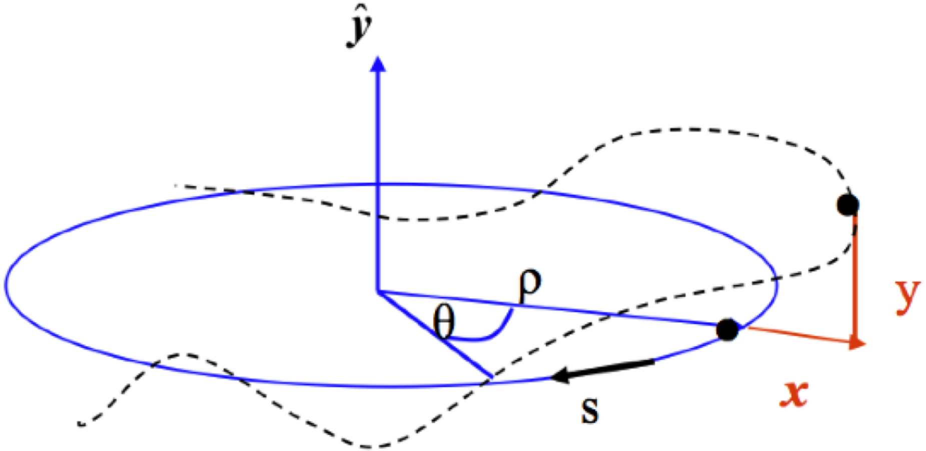
Equation of Motion

SLAC

- 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

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

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

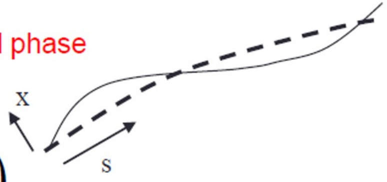


Betatron Oscillation

SLAC

- "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

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

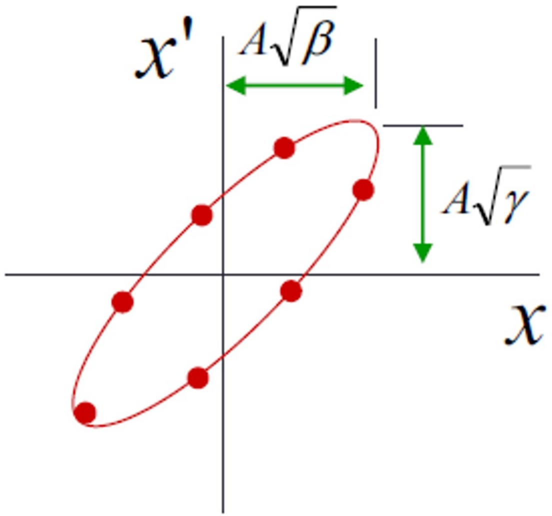
The "betatron function" $\beta(s)$ is effectively the local wave number and also defines the beam envelope.

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

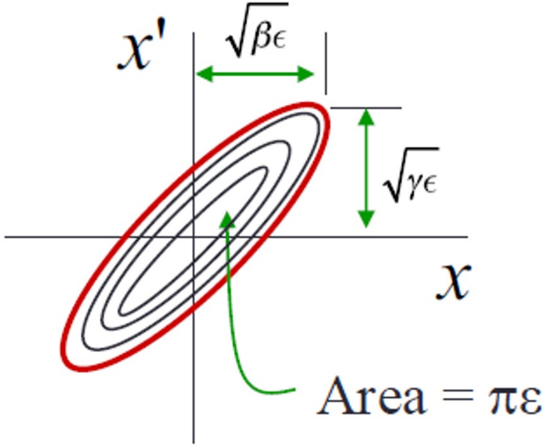


$$\gamma x^2 + 2\alpha x x' + x'^2 \beta = A^2$$
$$\text{Area} = \pi A^2$$
$$\beta\gamma - \alpha^2 = 1$$

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:



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

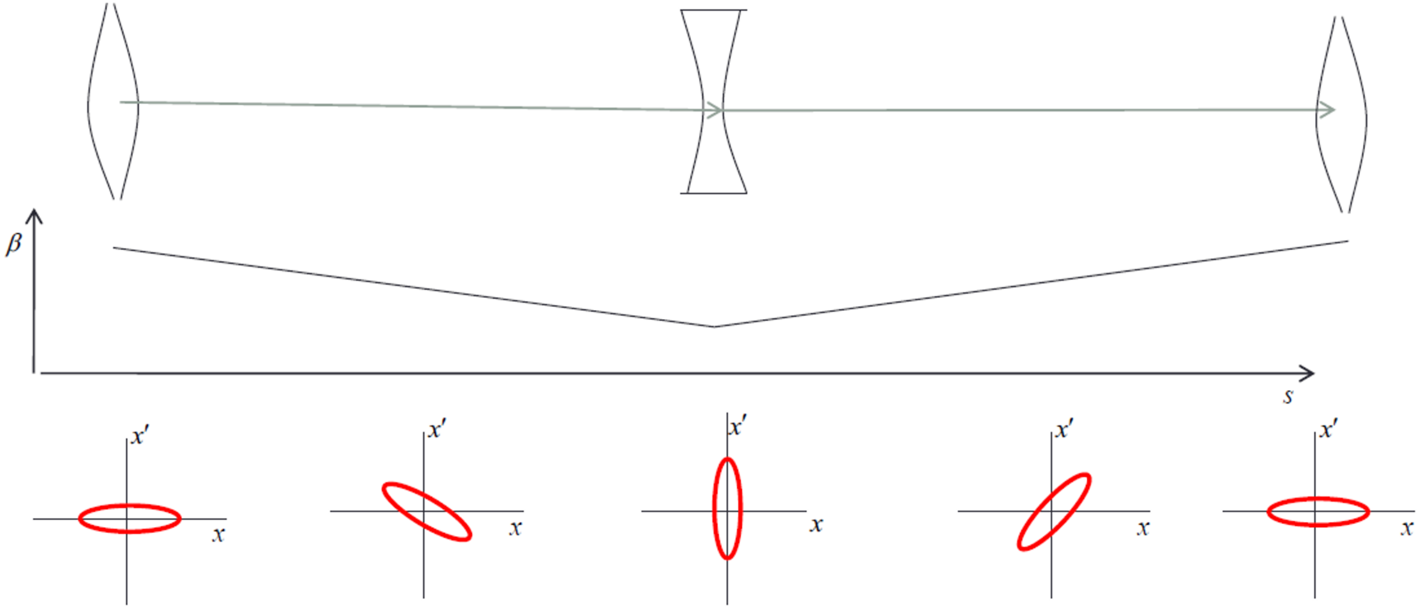
There are different definitions of emittance, but CERN generally uses the Gaussian definition

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

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

Emittance and Beam Distributions

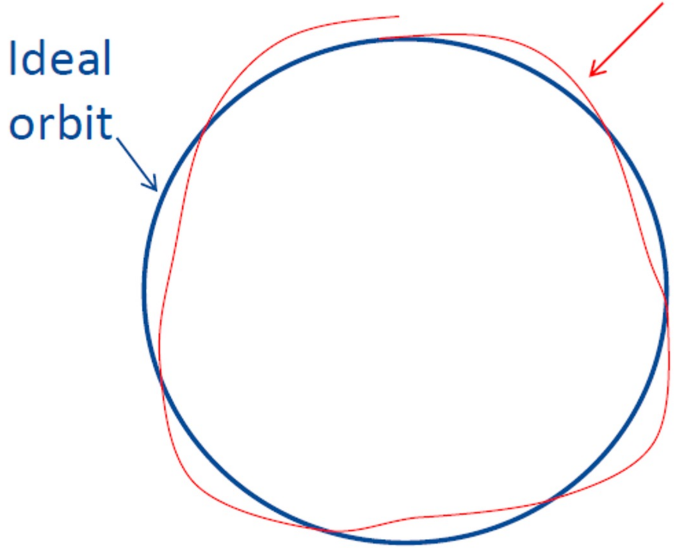
- As we go through a lattice, the bounding emittance remains constant



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

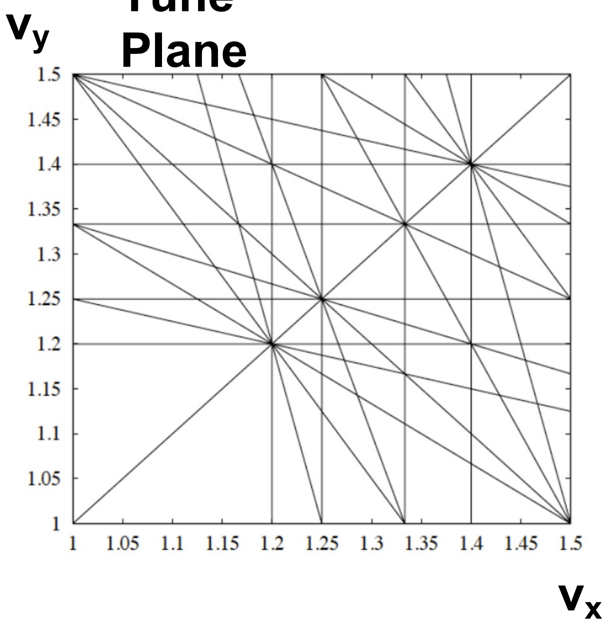
Tune, Stability, and the Tune Plane

- 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

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

- 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.

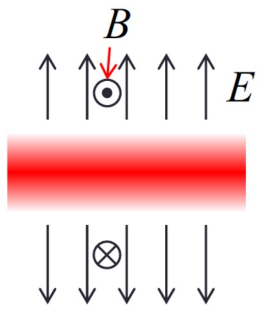
Tune Plane



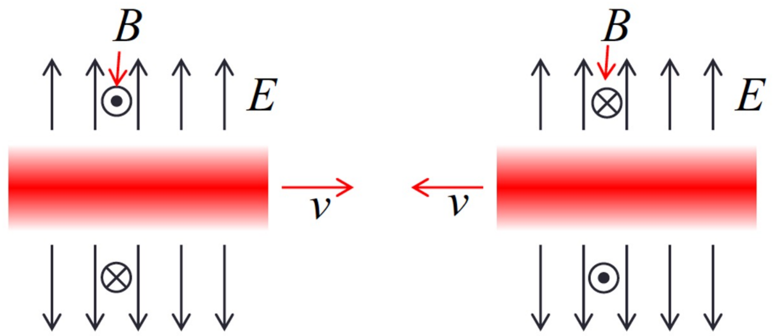
Tune Shift and Instabilities

- 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

-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

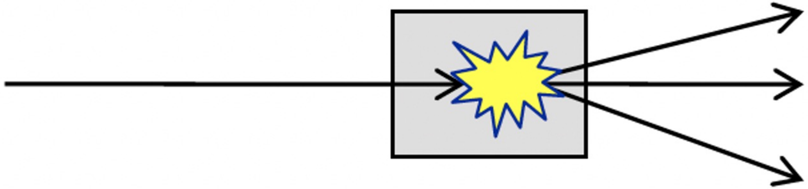
Static vs. Head-On

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

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

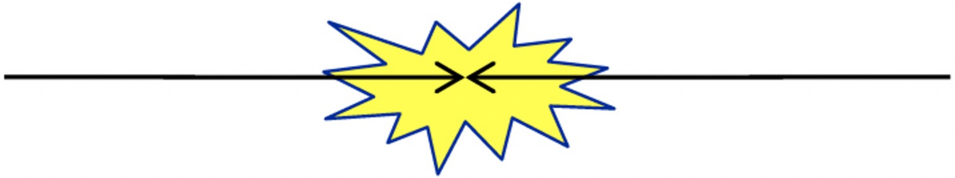
Bevatron used Cu target: p + n →p + n + p + pbar

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



If both beams have same momentum…

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



Luminosity of Colliding Beams

- Equally intense Gaussian beams

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

Number of Bunches → n_b

Particles per Bunch → N_b

Geometric Factor → R
- crossing angle
- hourglass effect

Revolution Frequency → f_{rev}

Transverse Size (RMS) → σ

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

Betatron function at collision point → β^*

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

Proportional to Energy → γ

want strong focusing → β^*

Normalized emittance → ε_N

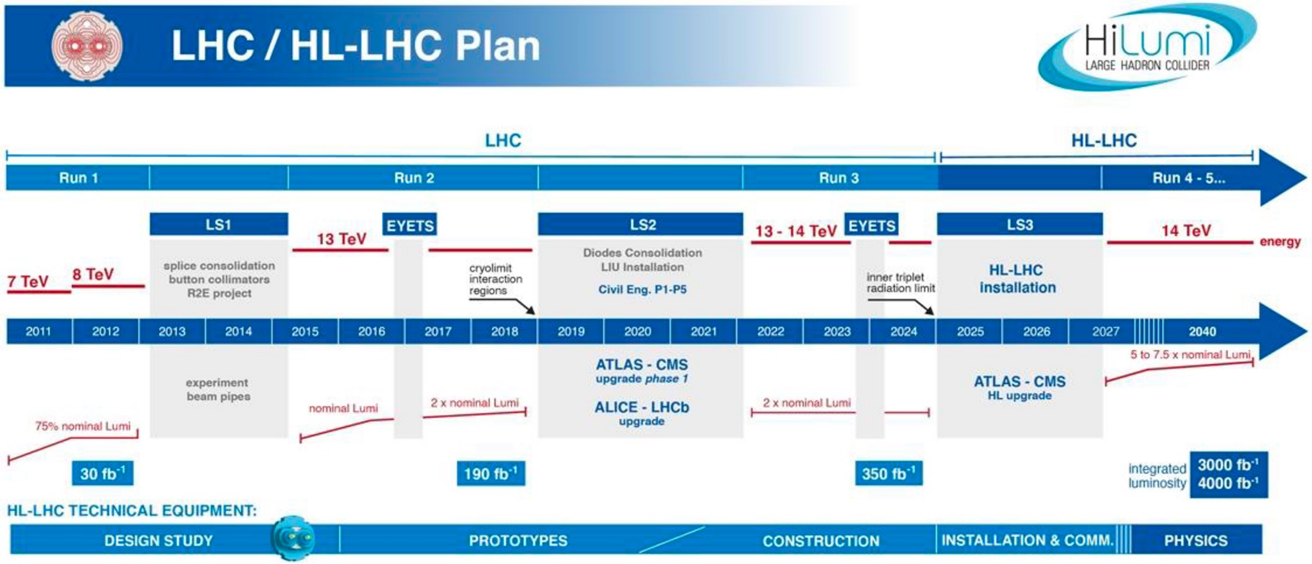
Outline

Part II

- Basic Accelerator Physics
- Future Directions

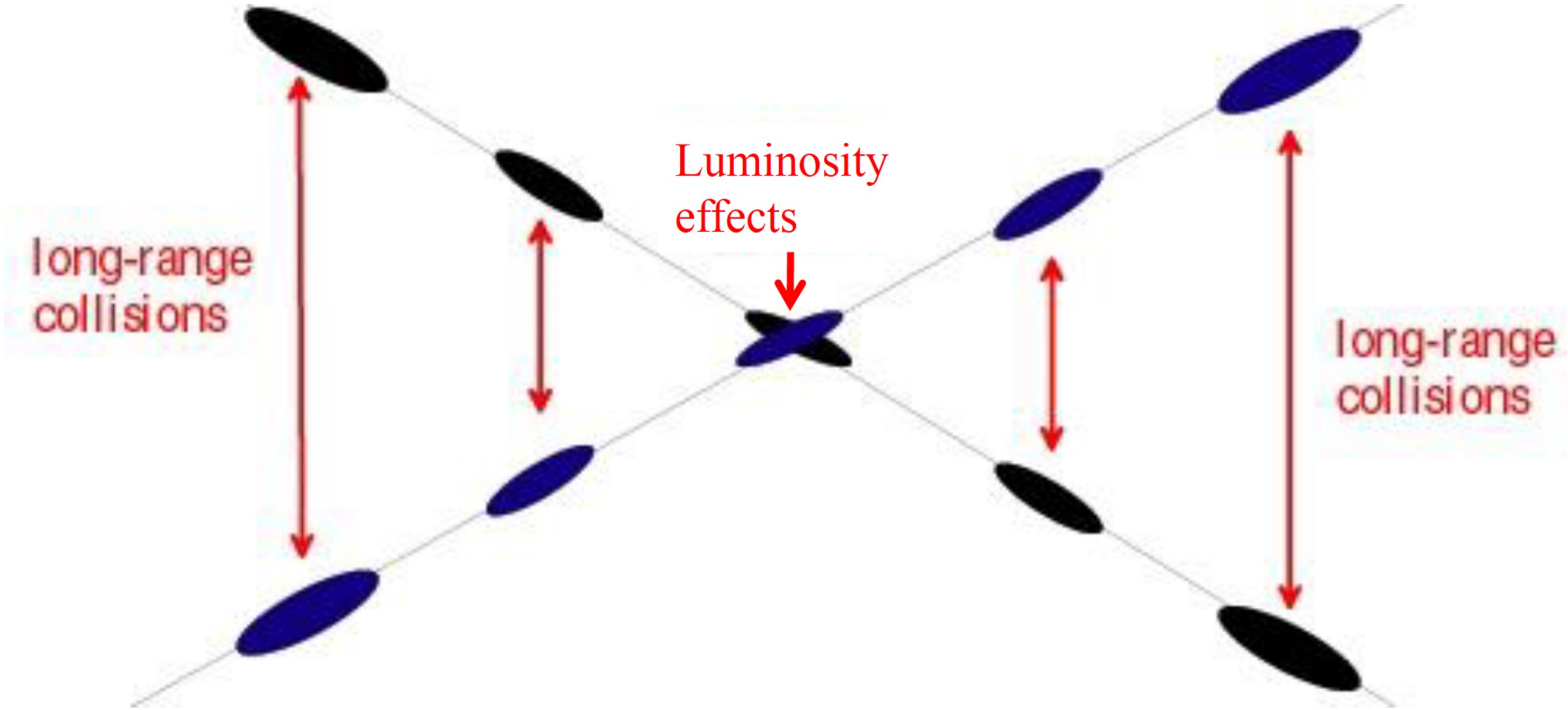
Future of LHC Research

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

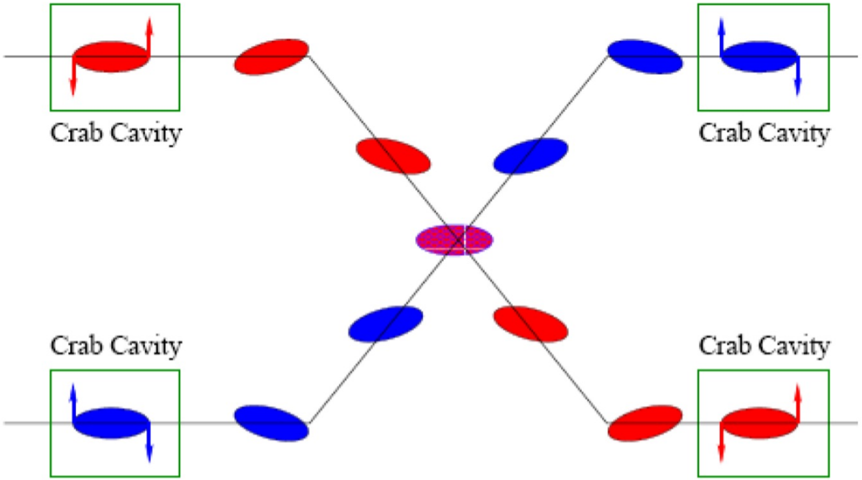


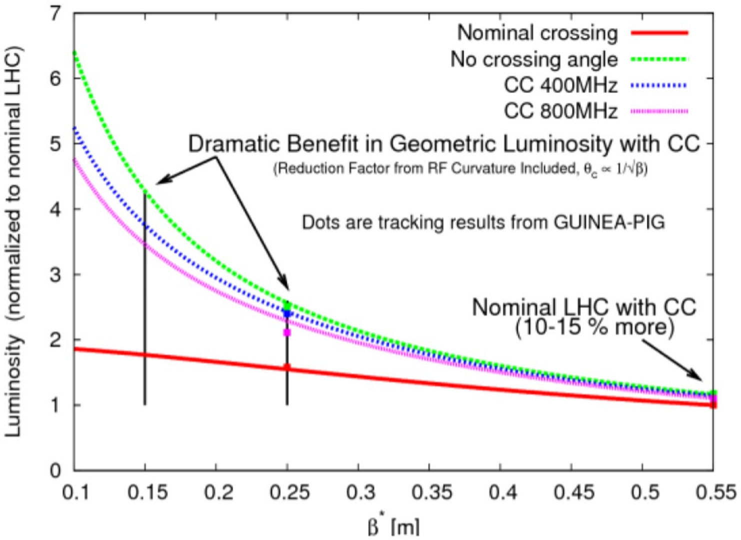
Examples: New focusing quads, upgrade to injector linac, CRAB Cavities….

Impact of Crossing Angle



Crab Cavities

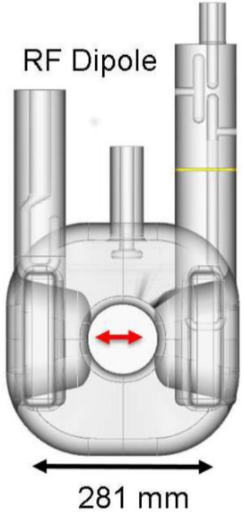


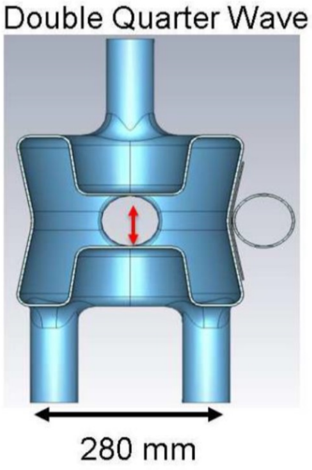


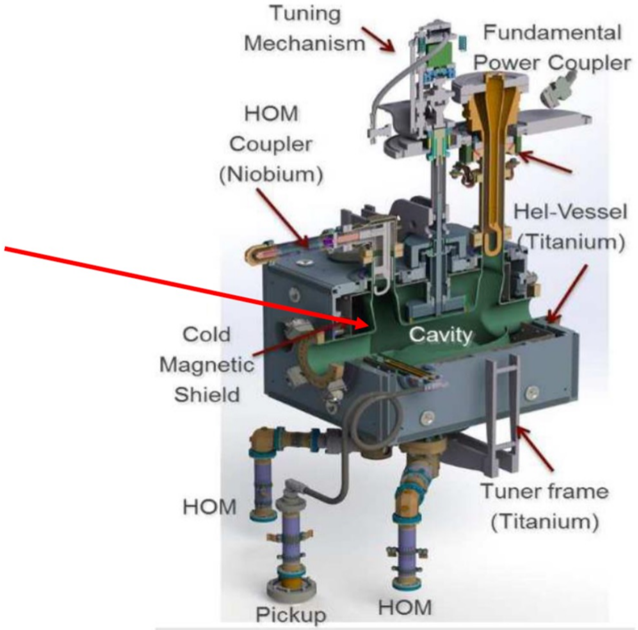
- Crab cavities apply a transverse kick so the bunches hit head on
- Challenge: need 400 MHz to prevent filamenting the bunch
  - VERY challenging to design these to fit in the ~20 cm between beam pipes!
- Long R&D program spearheaded by LARP

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







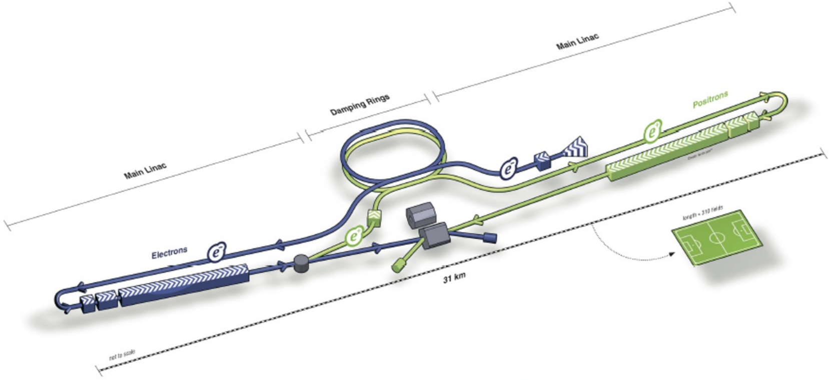
Linear vs. Circular

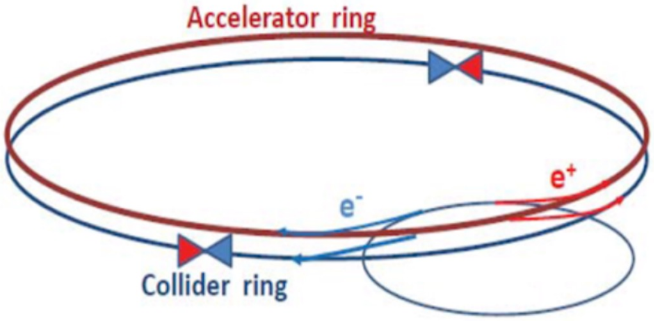
Linear e^+e^- colliders: ILC, C^3, CLIC

- 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

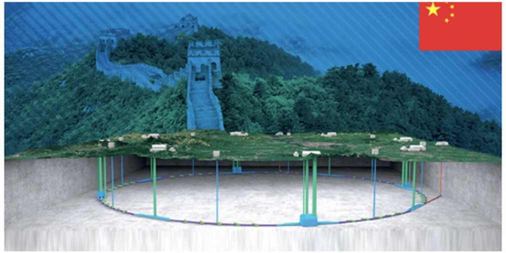




Future e⁺e⁻ Collider Proposals….

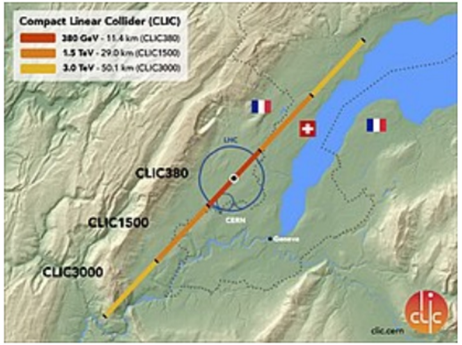
SLAC

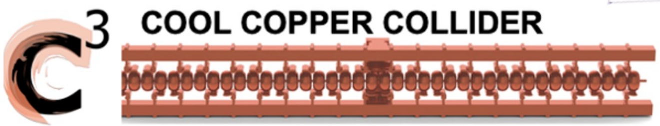
250/500 GeV



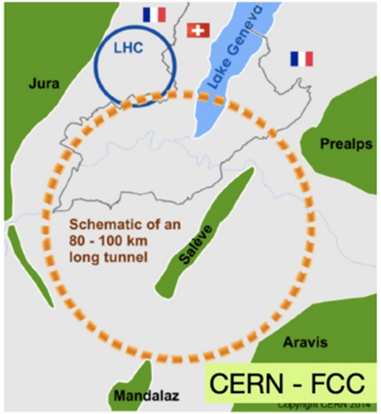
CEPC 240 GeV

CLIC 380/1500/3000 GeV





250/550 GeV
… > TeV

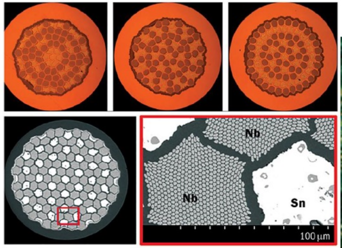


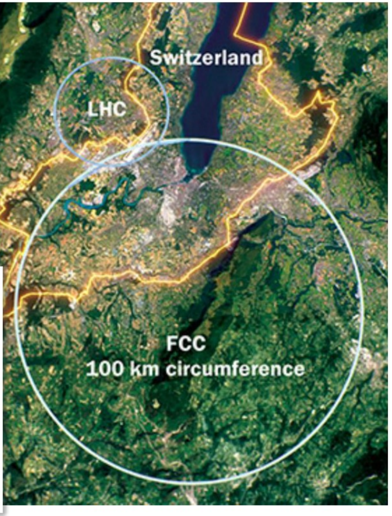
FCC-ee
240/365 GeV

Future *Muon and hh* Colliders

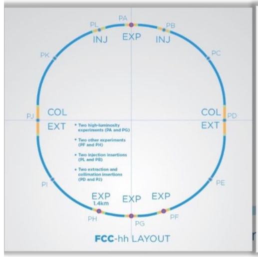
New magnet technology Nb_3Sn – **16 T** (vs **8 T** in the LHC with NbTi)

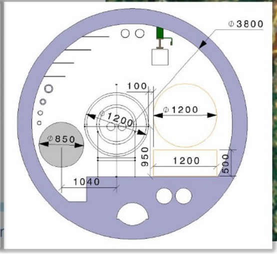
current record **14T** (CERN), Fermilab → **15 T**





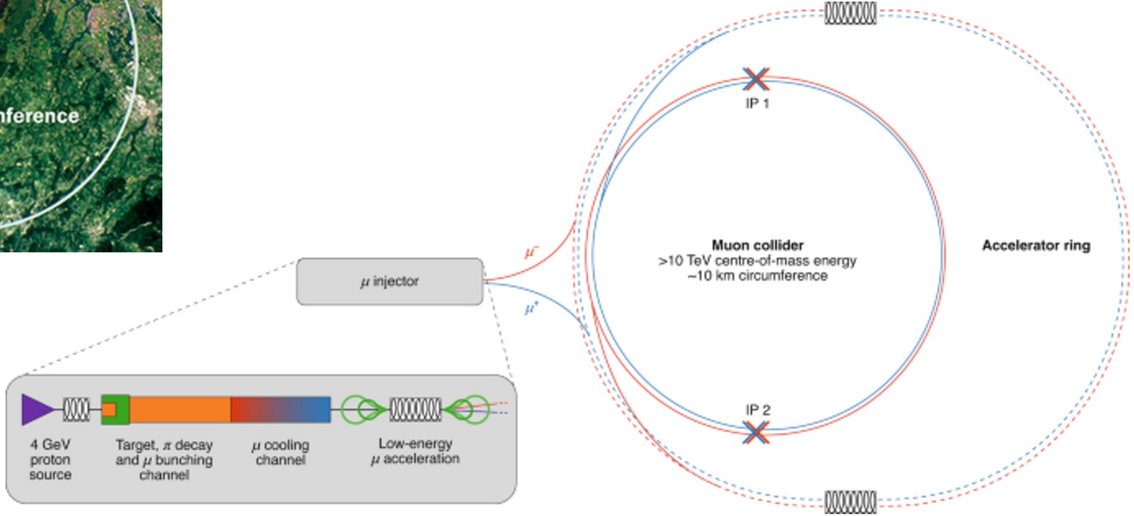
...either in a new or old tunnel





FCC-hh

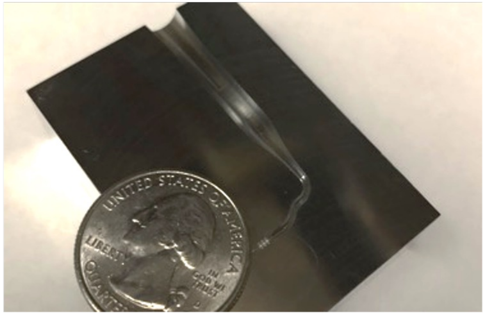
Muon Collider



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