Karlsruher Institut für Technologie

Vorlesung:

Teilchenphysik I (Particle Physics I)

Particle Accelerators

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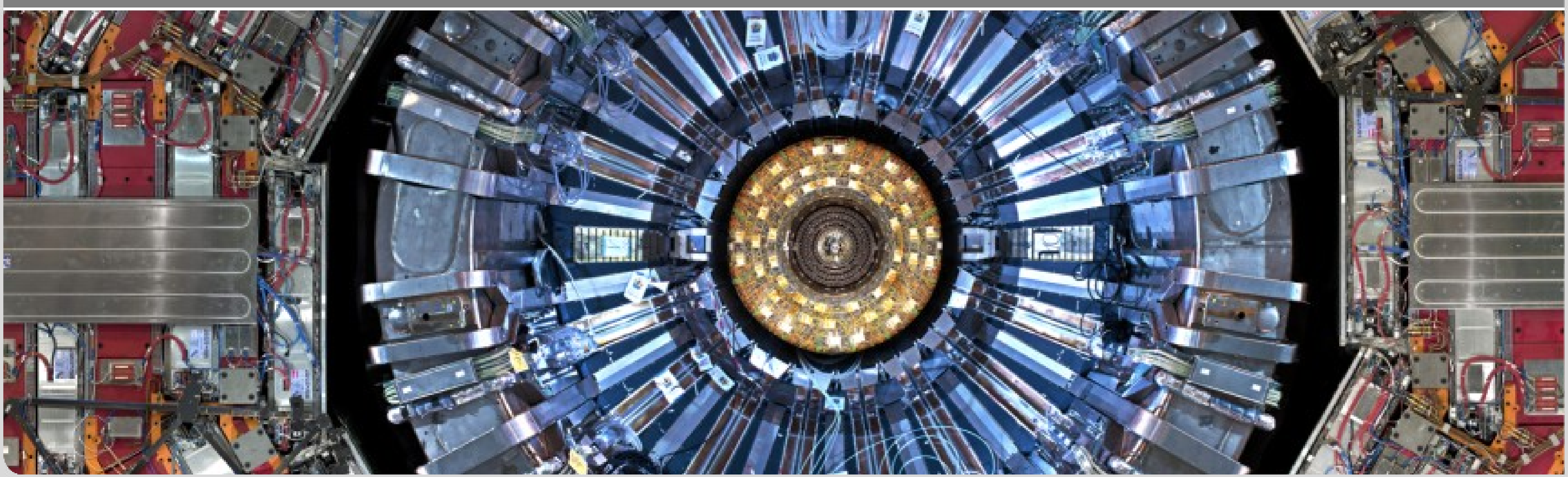
WS 20/21

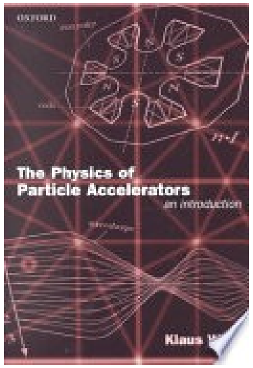


1. History
2. Basics principles
3. Detectors and Accelerators
    1. Interaction of particles with matter
    2. Simulation of particle interactions with Monte Carlo
    3. Detector Systems
    4. Accelerators

Literature

K. Wille, *Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen*, Springer Vieweg

K. Wille, *The Physics of Particle Accelerators*, Oxford University Press, 2000

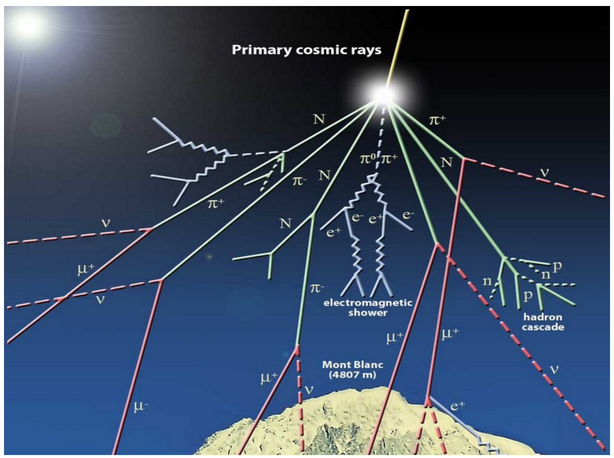


F. Hinterberger, *Physik der Teilchenbeschleuniger und Ionenoptik*, Springer (2008)

Motivation for Particle Accelerators

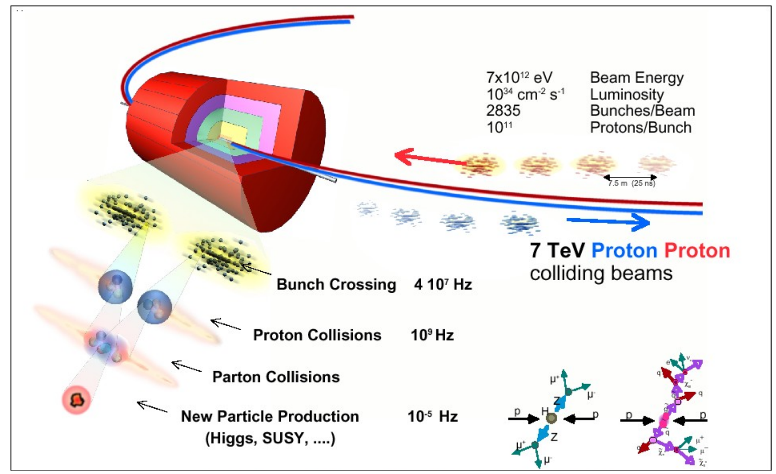
Nature delivers
ultra-high energy particles:

- Ultra-high energies
- complicated detection medium (atmosphere)
- large-area detectors required



Particle accelerators
deliver high-energetic particles under laboratory conditions:

- Perfect control of initial conditions
- events originate in one place
- compact, tailored detector designs



- Production of new, heavy particles: maximum mass = centre-of-mass energy
  $M = E_{CMS} / c^2$
- resolution of small structures: De-Broglie wave length of beam particles

$$\lambda = \frac{h}{p} = \frac{2\pi\hbar c}{pc} \rightarrow \lambda\,[\mathrm{fm}] \approx \frac{1.24}{p[\mathrm{GeV}]}$$

$$p = 1\,\mathrm{GeV} \quad \rightarrow \quad \lambda = 1.24 \cdot 10^{-15}\,\mathrm{m}$$
$$p = 1\,\mathrm{TeV} \quad \rightarrow \quad \lambda = 1.24 \cdot 10^{-18}\,\mathrm{m}$$

Basic Principle

The Lorentz force $\vec{F}_\mathrm{L} = q(\vec{E} + \vec{v} \times \vec{B})$

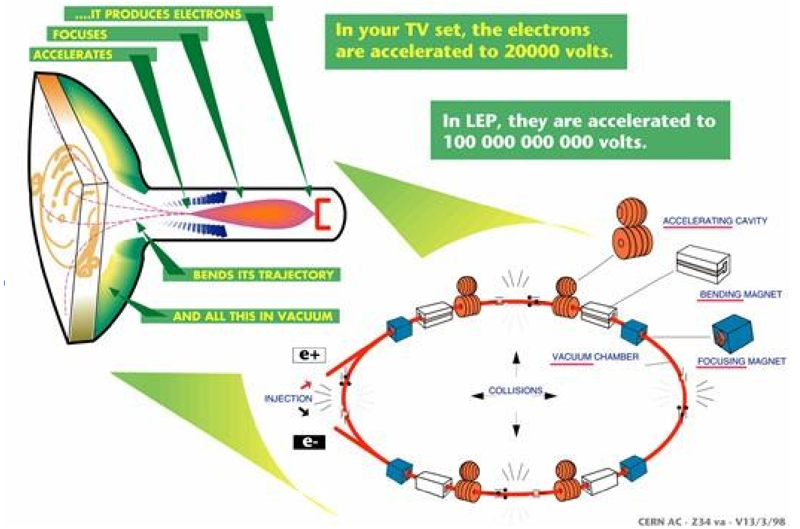
- **Acceleration** of charged partilces by electrical field(s)
- **Deflection** of charged particles by magnetic fields

Energy gain only from electrical fields:

$$\Delta E = \int_{s_0}^{s_0+d} \vec{F}_\mathrm{L} \cdot \mathrm{d}\vec{s} = q \int_{s_0}^{s_0+d} \vec{E} \cdot \mathrm{d}\vec{s} = qU$$

Acceleration voltage of 1 V corresponds to an energy gain of 1 eV

An Accelerator is a machine providing arrangements of electrical and magnetic fields to accelerate, store and focus charged particles.

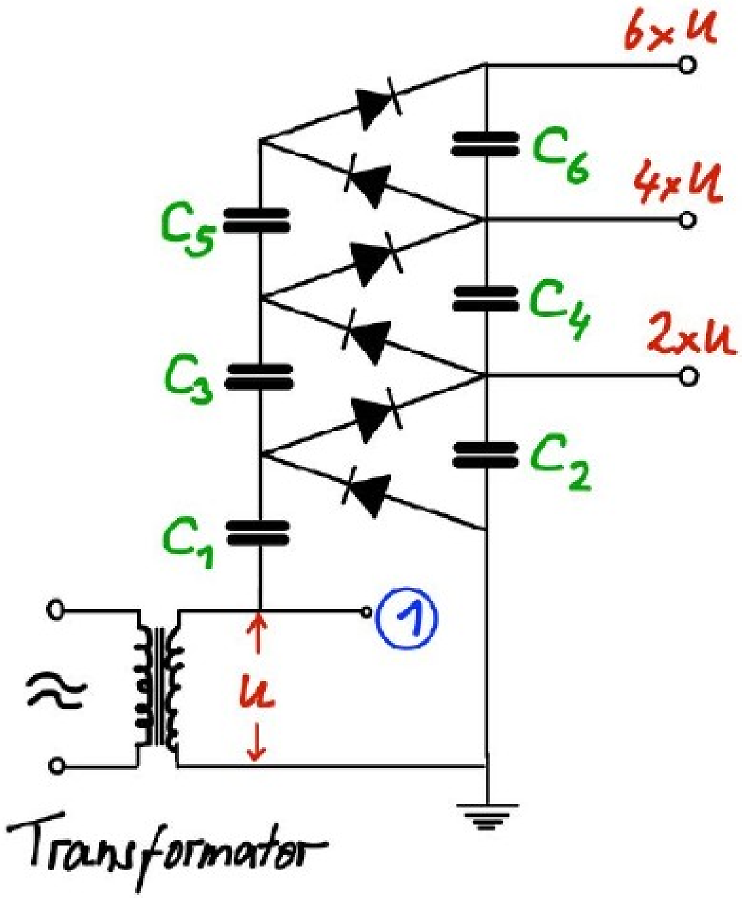


http://cds.cern.ch/record/39726

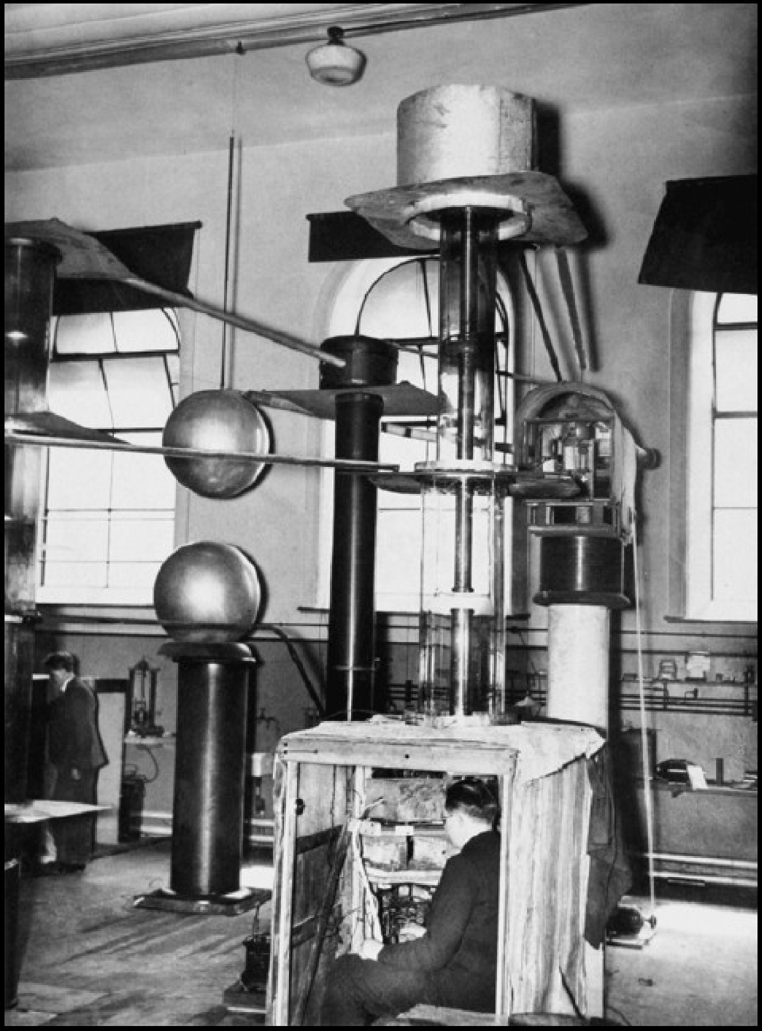
Historical Accelerators

Cockcroft-Walton

- 1930s; up to 4 MV, μs pulses of up to 100 mA



source: lecture on Accelerator Physics by Anke-Susanne Müller

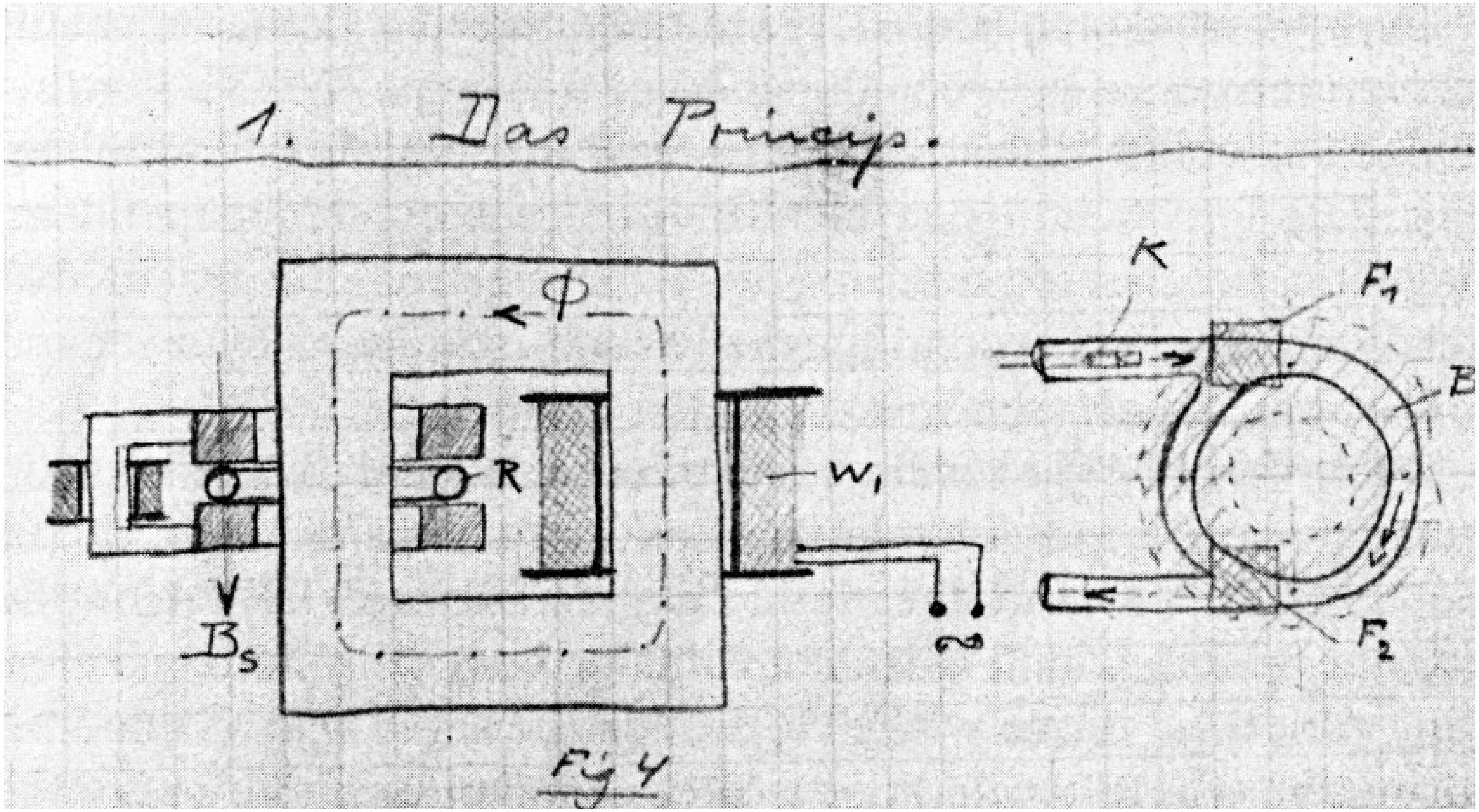


Cockroft and Waltons elektrostatischer Beschleuniger mit Cockroft “im Labor”

http://www.accelerators-for-society.org/about-accelerators/timeliner/img/1931.png

The Betatron

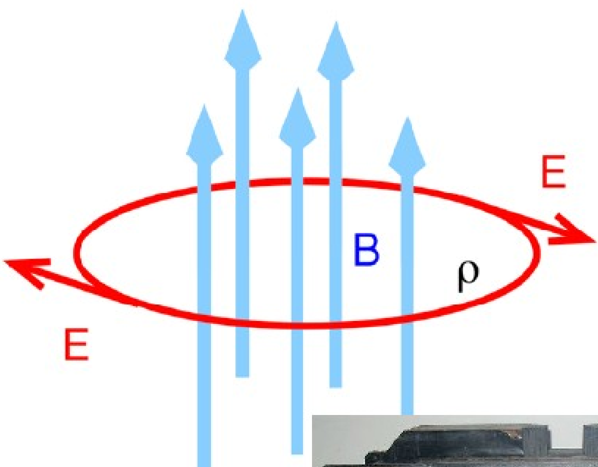
- Wideröe's "ray transformer"



E.J.N. Wilson, An Introduction to Particle Accelerators, Oxford University Press, 2001

Betatron (2)

- Wideröe's "ray transformer": exploiting $\oint \vec{E} \cdot d\vec{r} = -\int\int \frac{d}{dt} \vec{B} \cdot d\vec{a}$



Betatrons are still widely in use today (medical applications)

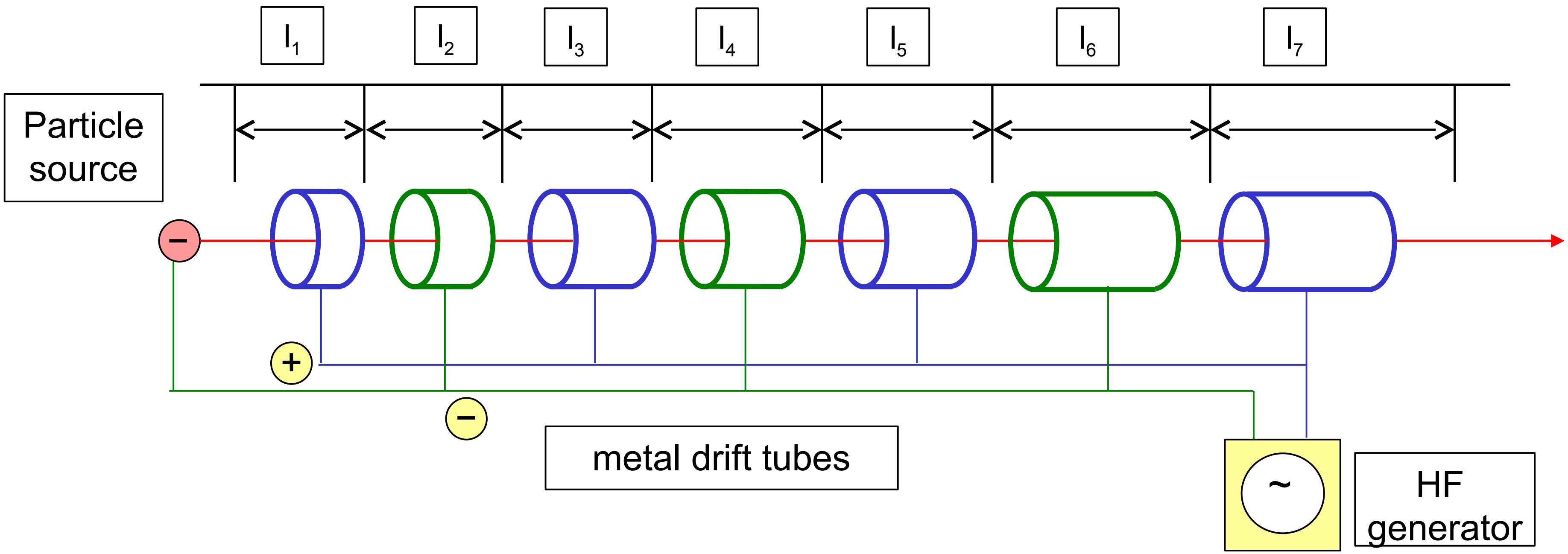
Very compact systems
example: 30 MeV with 0.1 m radius

http://www.jme.co.uk/JME-Products-Betatron.aspx

http://commons.wikimedia.org/wiki/File:Betatron_6MeV_(1942).jpg

Linear Accelerdator ...

… the initial stage of every modern accelerator



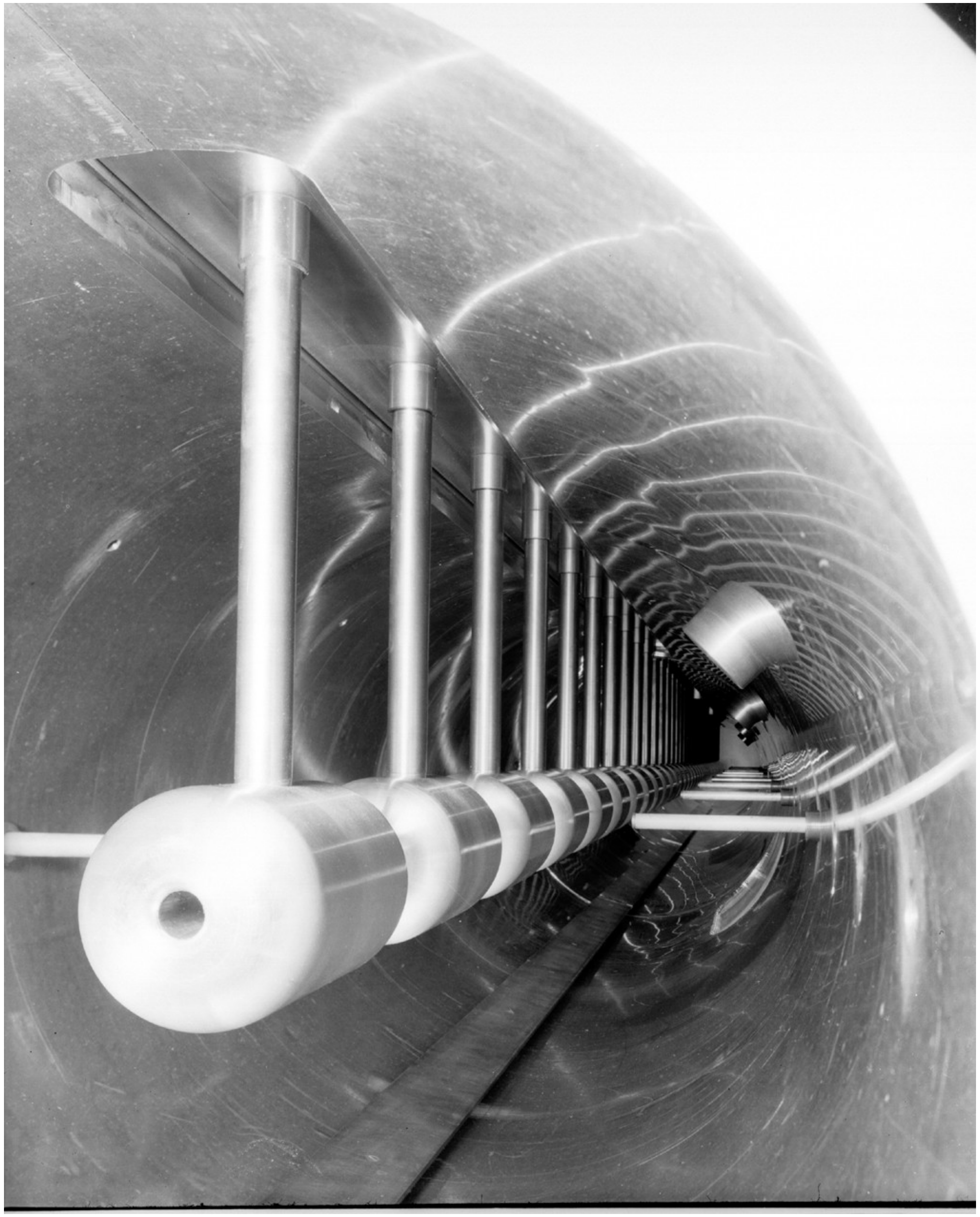
– particles from source are acceletated in potention of first drift tube

– voltage is inverted while particle is inside the first tube

– particles leave first drift tube and are accelerated towards the scond tube

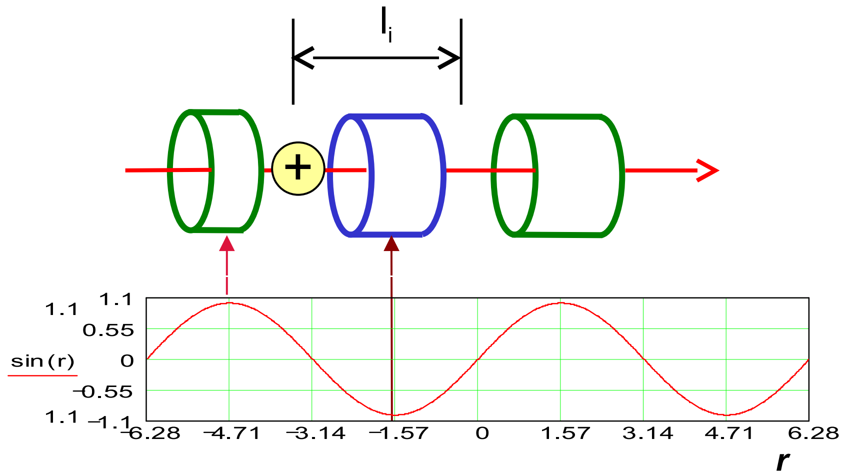
– lengths of tubes and distance between them increase, because speed of (low-energy) particles increases

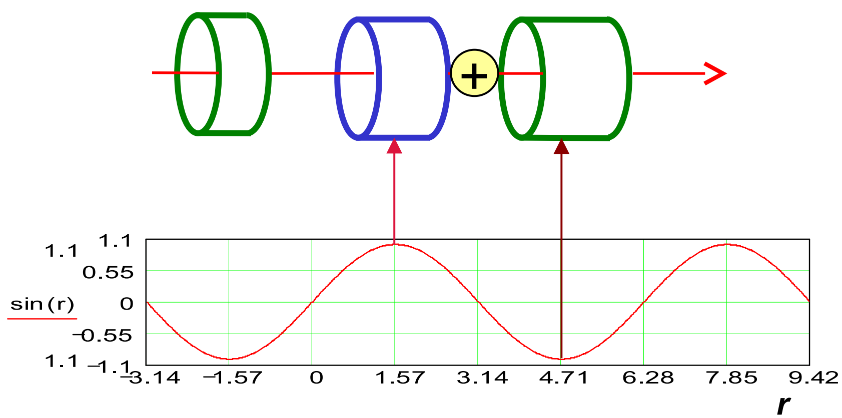
Linac Structure



CERN Micorcosm

Linear Accelerator - principle





Energy after passing drift tube *i*

$$E_i = iqU_0 \sin(\Psi_s)$$

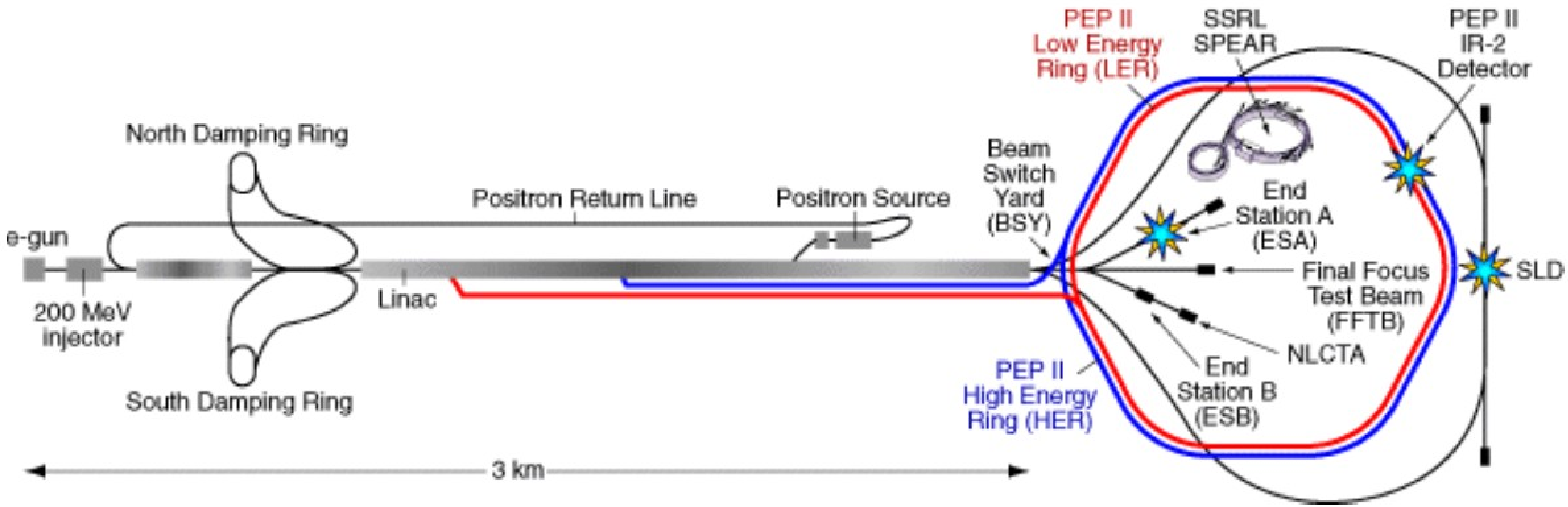
- $r = x\, k_{HF}(x)$ is **phase** of particle
  k_{HF} is the wave number of high voltage
- U_0 is maximum **voltage** of HF generator
- Ψ_s is phase of particle relative to HV

Only particles with phase $\Psi \approx \Psi_s$ can be accelerated

→ leads to **particle bunches**

The (so far) largest Linear Accelerator

- SLC at SLAC: up to 50 GeV electrons and positrons



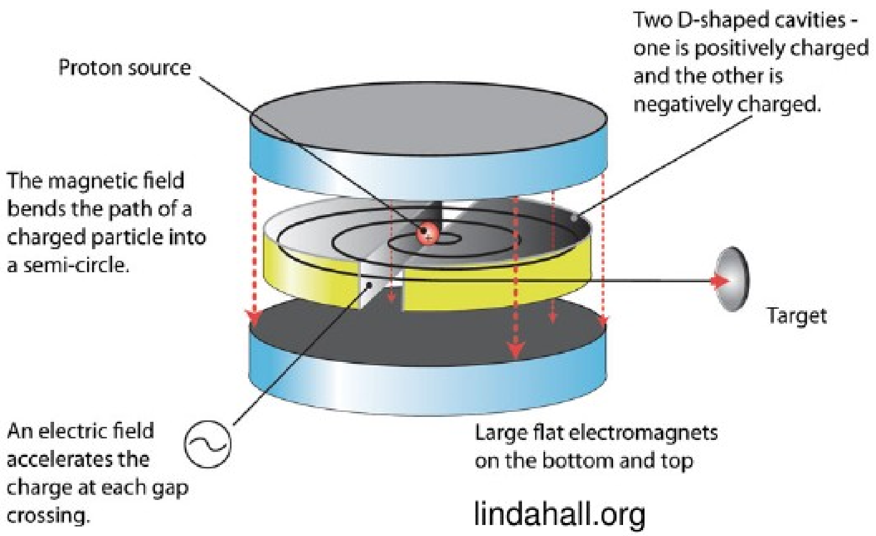
http://erlangen.physicsmasterclasses.org/exp_forsc/exp_forsc_11.html

operated on the Z resonance, precision electroweak physics with polarized beams

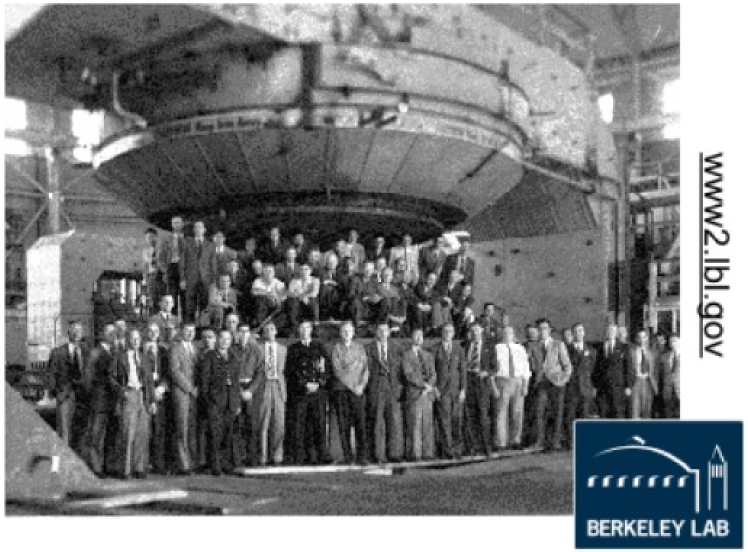
Circular Accelerators: the Cyclotron

(M.S. Livingston, E.O. Laawrence, 1930)

- ***Strong magnetic field*** bends path of particles on circular orbit
  $\rightarrow$ ***repeated acceleration*** within ***same structure***
- Design: ***D-shaped poles***
  $\rightarrow$ particle on spiral trajectory



Berkeley: 184-Zoll-Synchrozyklotron



Still used today for ***protons/ions beams of medium energy***

- Nuclear physics
- Cancer therapy
- Material science (e. g. ZAG Zyklotron AG, KIT Campus Nord)

Cyclotron Frequency

Ansatz: ***Lorentz force*** $\vec{F}_L(\vec{E}=0)$ ***= centripetal force*** $\vec{F}_Z$

Non-relativistic approximation:

$$qvB = m\frac{v^2}{r} \quad \Rightarrow \quad \omega = \frac{v}{r} = \frac{qB}{m}$$

- Characteristic ***cyclotron frequency*** (independent of momentum)
- Typcial values for protons and $B = 2\,\mathrm{T}$: $\omega = 1.9 \cdot 10^8\,\mathrm{s}^{-1}$ $\rightarrow \nu = 30.5\,\mathrm{MHz}$ (radio frequency)
- Relativistic calculation:

$$\vec{F}_L = \frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}(\gamma m\vec{v}) \quad \Rightarrow \quad \omega = \frac{qB}{\gamma m}$$

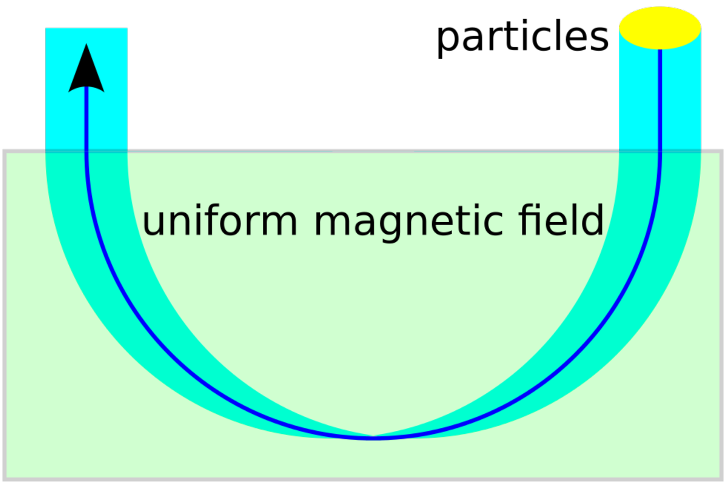
Curvature radius R (cf. tracking): $R = \frac{p[\mathrm{GeV}]}{0.3qB[\mathrm{T}]}$

- Typical values $R = 0.5\,\mathrm{m}$, $B = 0.5\,\mathrm{T}$: maximum momentum $p = 75\,\mathrm{MeV}$
- Maximum energy limited by ***size (and strength) of magnet***, typical sizes up to few $10\,\mathrm{MeV}$

Weak Focusing in homogeneous B Field

Particles of the same energy
have the same curvature radius
in an homogeneous B field

→ particle trajectories with
slightly displaced positions
cross twice per turn



https://en.wikipedia.org/w/index.php?curid=35084821

"weak focusing"

used in cyclotrons and early synchrotrons

Accelerator Physics

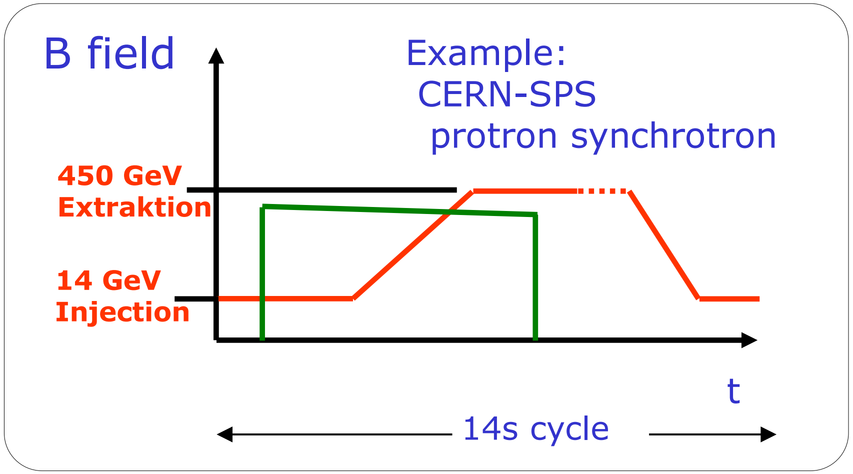
- a brief overview -

Circular Accelerators: the Synchrotron

new idea:

increase magnetic field syncronous to particle momentum (M. Oliphant, 1943)

keep beam radius ~constant,
magnetic field only in beam tube



→ **"Synchrotron"**

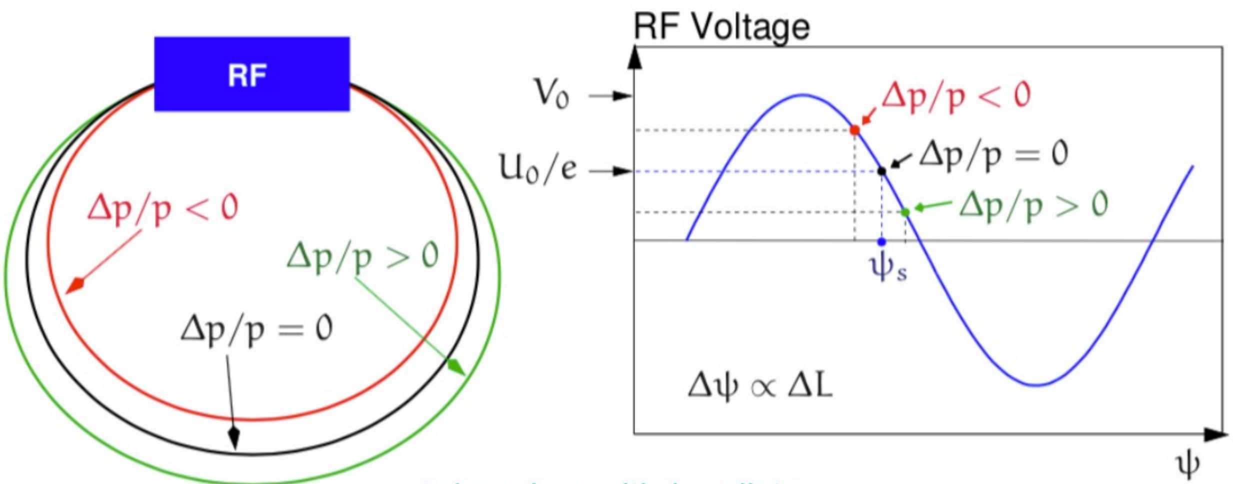
Circular Accelerators: the modern Synchrotron

breakthrough discovery: Phase Focussing (Veksler 1944, McMillan 1945)

Orbit length *L* in a circular accelerator is given by RF frequency f_{RF}:

L is a multiple *h* of the "RF wavelength" $\lambda_{RF} = c / f_{RF}$

– h is called "harmonic number"



➜ *bunches with λ_{RF} distance*

➜ *timing is crucial*

Principle
(for relativistic particles) :

- fast particles arrive later
  → receive less acceleration
- slow particles arrive eariler
  → recive more acceleration

Phase of particles oscillates around optimal phase, the **"stabe phase" Ψ_s**

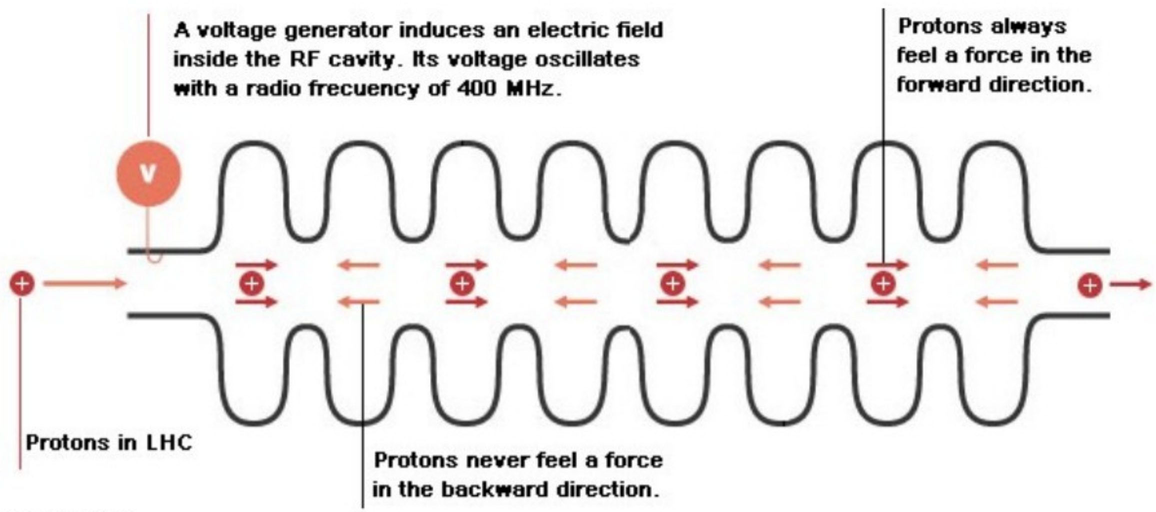
"Synchrotron Oscillation"

Phase of particles adjusts itself to compensate energy losses → **Phase Focusing**

also: Changes of beam energy by inceasing the magnic bending field

Accelerating RF Cavities

- Acceleration of particles by alternating electrical field in a resonating cavity
- enforces and retains bunch structure of beam
- radio frequency @ LHC: 400 MHz

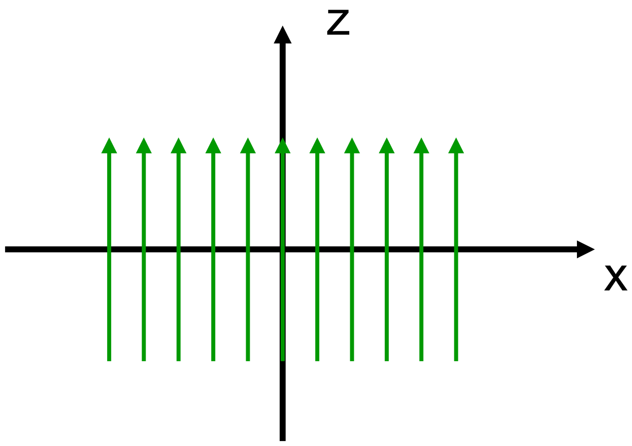


lhc-closer.es

- RF power generated in high-power klystron (by electron-density modulation) induced into cavities via RF wave guides

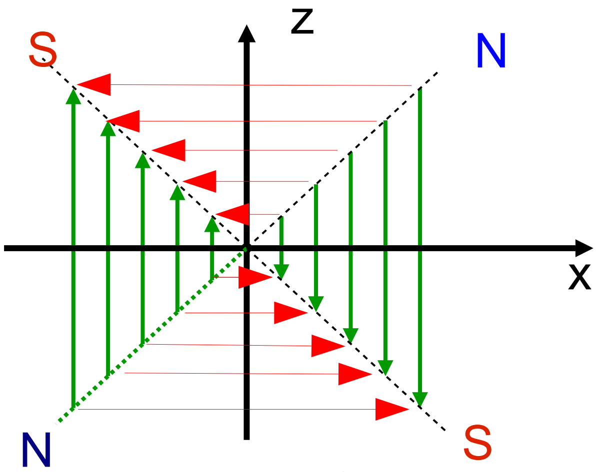
Synchrotron: strong focusing

another important ingredient: use of **quadrupole magnets** to **focus beam**
(Chrostofilos 1950, Courant, Livingston & Synder 1952)



Dipol B field

constant field across aperture;
provides bending field



quadrupol B field
zero field in centre,
linear growth of field strength
with off-set from centre

for e⁻ into image plane:
– focusses horizontally
– de-focusses vertically

→ use **pairs of quadrupoles**
to achieve overall focussing

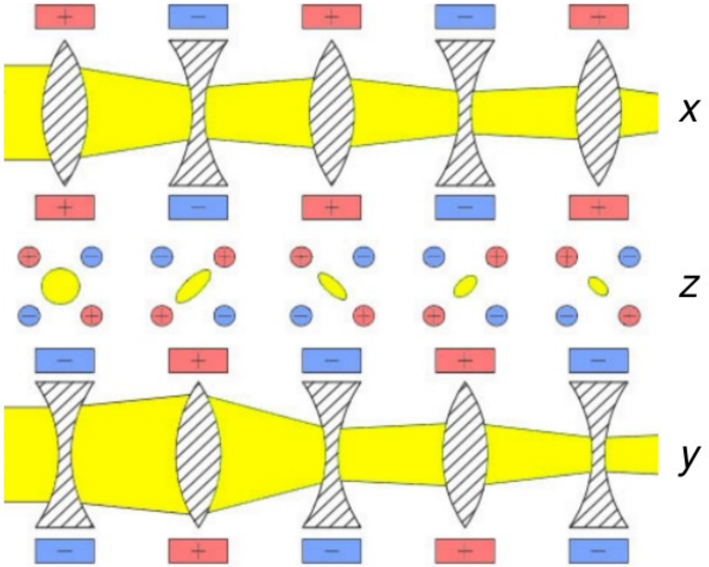
"Alternate Gradient"

additional **sextupole** and **octupole**
magnets are needed to control beam optics

Strong Focussing: principle

- Series of quadrupole magnets with ***alternating field gradients*** in *x*, *y*
- Second magnet in ***focal point*** of first, and so on

→ **beam is focussed in** x **and** y

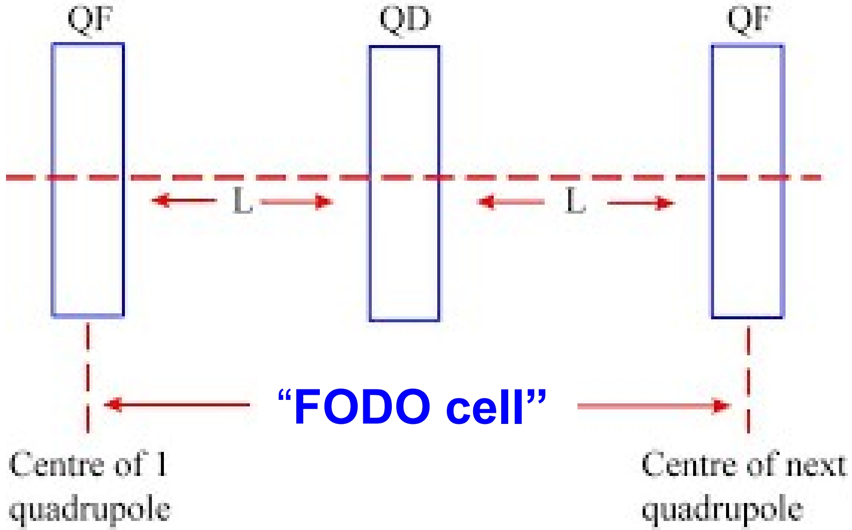


optical analogy

sequence of elements:

Focusing - o - **D**efocusing - o -

– drift – – drift –



"strong focusing"
in modern synchrotrons

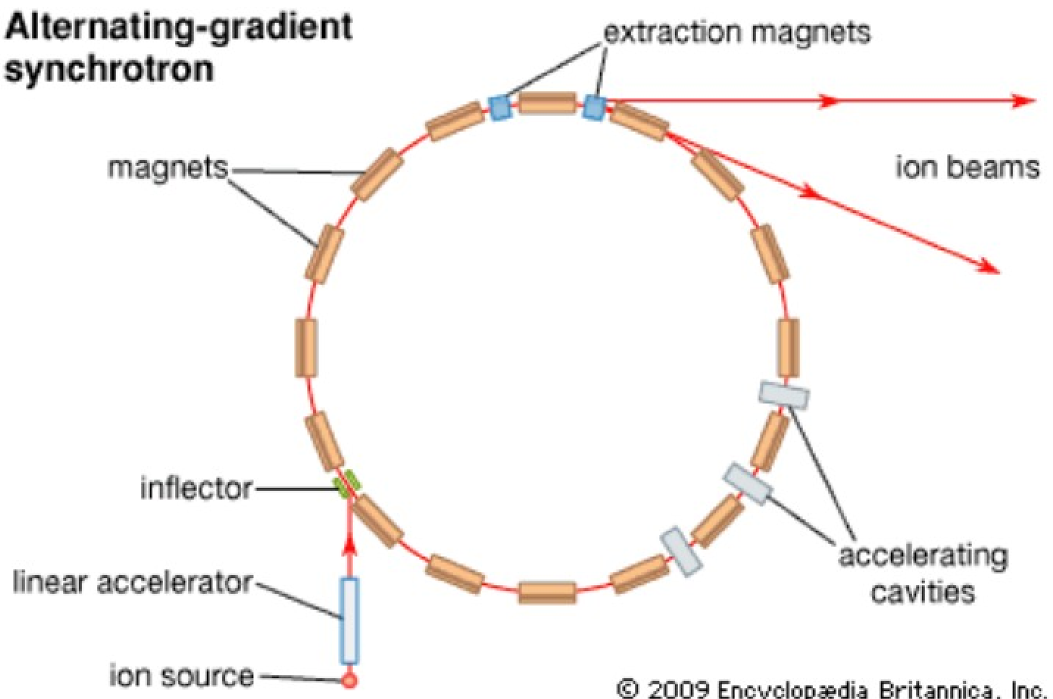
Modern Synchrotron

Alternating-gradient principle reduces beam size and increases energy aperture

beam optics charachterized by "Momentum Compaction Factor" α_c

$$\frac{\Delta x}{x} = \frac{\Delta L}{L} = \alpha_c \frac{\Delta p}{p}$$

x: beam displacement
L: orbit length
p: momentum



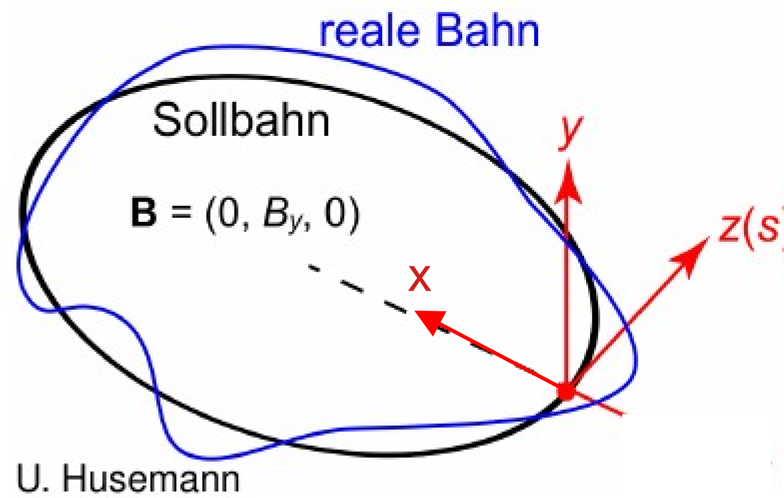
britannica.com

Components of a synchrotron
- deflection magnets (dipoles)
- focussing magnets (quadrupoles, sextupoles and octupolse)
- injection magnets (pulsed)
- extraction magnets (pulsed)
- RF acceleration cavities
- vacuum system
- beam diagnostics
- control system
- powerful power supplies

Transverse Beam Optics

Ensemble of particles, ***not*** all on ideal circular orbit

- (Co-moving) coordinate system:
  - ***beam direction z***
  - transverse ***deviation from ideal trajectory x, y***
- Expansion of particle trajectory for ***small deviations***



Effect of ***Lorentz force*** on particles in magnetic field $\vec{B} = (0, B_y, 0)$

- Inverse radius of curvature: $\boxed{\frac{1}{R(x,y,z)} = \frac{q}{p} B_y(x,y,z)}$
- Beam dimensions $\ll R \rightarrow$ expansion of B_y in x (analogue for y)

$$\begin{aligned}
\frac{q}{p} B_y(x,y,z) &= \frac{q}{p} B_y(0,y,z) + \frac{q}{p}\frac{\partial B_y(0,y,z)}{\partial x}\cdot x + \frac{1}{2}\frac{q}{p}\frac{\partial^2 B_y(0,y,z)}{\partial x^2}\cdot x^2 + \ldots \\
&= \underbrace{\frac{1}{R}}_{\textbf{dipole}} + \underbrace{k\cdot x}_{\textbf{quadrupole}} + \underbrace{\frac{1}{2} m\cdot x^2}_{\textbf{sextupole}} + \ldots
\end{aligned}$$

Linear Transverse Beam Optics

Linear transverse beam optics

$$\boxed{\frac{q}{p}B_y(x,y,z) = \frac{q}{p}B_y(0,y,z) + \frac{q}{p}\frac{\partial B_y(0,y,z)}{\partial x}\cdot x} + \frac{1}{2}\frac{q}{p}\frac{\partial^2 B_y(0,y,z)}{\partial x^2}\cdot x^2 + \ldots$$

$$\boxed{= \frac{1}{R} + k\cdot x} + \frac{1}{2}m\cdot x^2 + \ldots$$

- Terminate after linear term: deflecting force ***constant*** (dipole field) or ***linear*** with distance x from design trajectory (quadrupole field)
- Realistic accelerators: ***corrections*** by higher multipoles

Equation of motion in x in co-moving coordinate system

(assumption: storage ring, no change of momentum)

$$\boxed{x''(s) + \left(\frac{1}{R^2(s)} - k(s)\right)x(s) = 0}$$

differential equation of **Hill's type**

– R(s), k(s): periodic functions in distance s along trajectory reflecting "magnetic lattice" of the machine

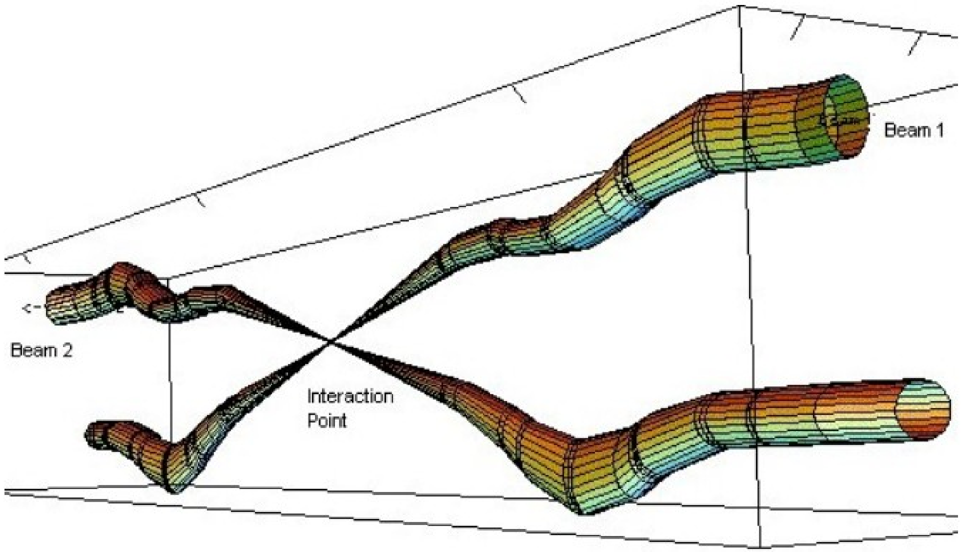
Solution:

$$\boxed{x(s) = \sqrt{\epsilon\beta(s)}\cos\left[\Psi(s)+\phi\right]}$$

- β(s): betatron function
- ε: emmitance
- Ψ(s): phase advance

Describes oscillation around ieal orbit ("betatron oscillations")

Betatron Oscillation



3D-view of the betatron envelope around an interaction point at the LHC

Betraton function $\boldsymbol{\beta(s)}$

(also: 'beta function', 'amplitude function')

- Quantifies deviation from ideal orbit
- Depends on ***beam focus*** along *s*
- Important characteristic quantity: β^* value of β function ***at interaction point***

value of β* during LHC Run 2: 30 cm

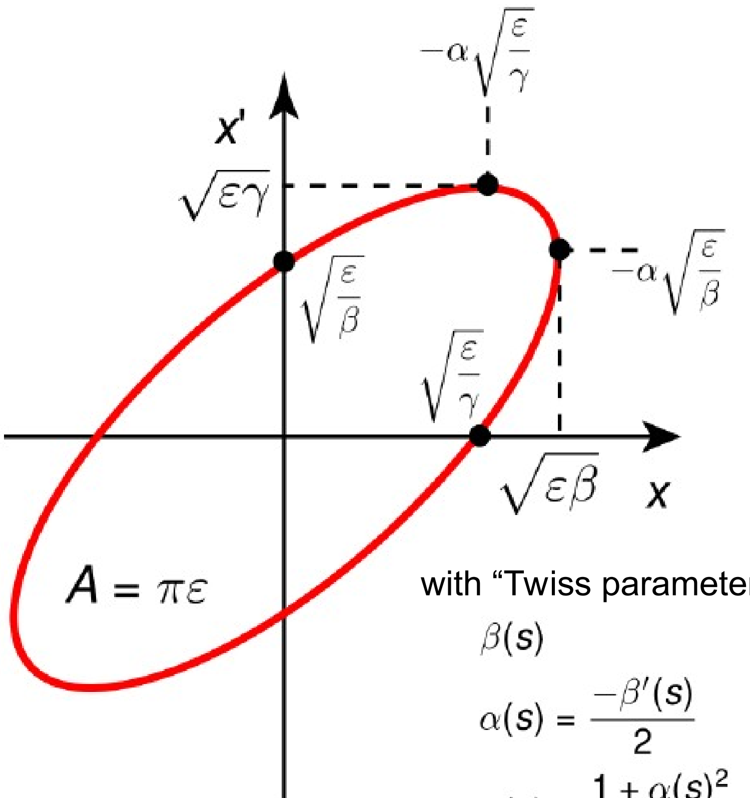
Phase Space and Emmittance

Phase space of beam given by $x(s)$ and $x'(s)$ ($\propto p$)

- Solution to Hill's equation: ***ellipse*** in phase space
- Emittance ϵ proportional to area of ellipse: $A = \pi\epsilon$

Liouville's theorem: particle density in phase space is constant for conservative forces

- Typically (approximately) the case in storage rings
- During fill, phase space ***deformed*** but ***density conserved***



with "Twiss parameters"

$\beta(s)$

$$\alpha(s) = \frac{-\beta'(s)}{2}$$

$$\gamma(s) = \frac{1+\alpha(s)^2}{\beta(s)}$$

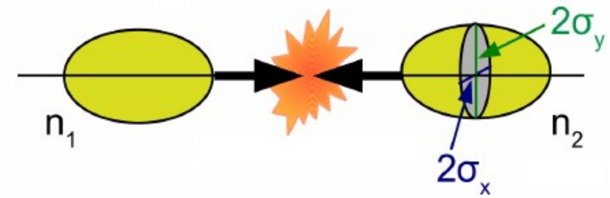
Emmittance

- Interpretation: quantifies ***spread in location and momentum of beam particles*** within ensemble (storage ring: ***ensemble = bunch***)
- $\epsilon \propto 1/p$: use ***normalised emittance*** $\epsilon_n = \gamma\epsilon$ (independent of beam energy)
- Example LHC 2016: $\epsilon_n = 2.6\,\mu\text{m} \rightarrow \sqrt{\epsilon\beta^*} = 12.3\,\mu\text{m}$ (cf. https://lpc.web.cern.ch/lumi2.html)

Luminosity of a collider

In an accelerator with counter-rotating bunches of particles, the luminosity is given by the bunch parameters:

$$\mathcal{L} = f \cdot n_b \cdot \frac{N_1 \cdot N_2}{4\pi\sigma_x\sigma_y}$$



- N_1, N_2 : number of particles per bunch
- σ_x, σ_y : bunch dimensions in *x* and *y* directions
- f : collision frequency
- n_b: numer of bunches

$\mathcal{L}$, the **instantantaneous luminosity**, is related to the **interaction rate** of a process with cross section σ by $\frac{dN}{dt} = \mathcal{L} \cdot \sigma$

The **integrated luminosity**, $L_{\mathrm{int}} =: L = \int \mathcal{L}\, dt$ is related to the total number of observed events in a data set

unit: [L] = cm^{-2}, conveniently also 1/fb = 10^{39} cm^{-2}

interpretation: a dataset of 1 fb^{-1} contains (on average) one event of a process with cross section 1 fb

Luminosity: Emmitance and Beta function

Impact of emittance on ***luminosity***

- Gaussian beam profile: betatron function of particles that are 1 standard deviation σ off the ideal orbit

$$\sigma(s) = \sqrt{\epsilon\beta(s)} \quad \rightarrow \quad \beta(s) = \frac{\sigma^2(s)}{\epsilon}$$

Strong quadrupoles near the interaction points locally reduce β;

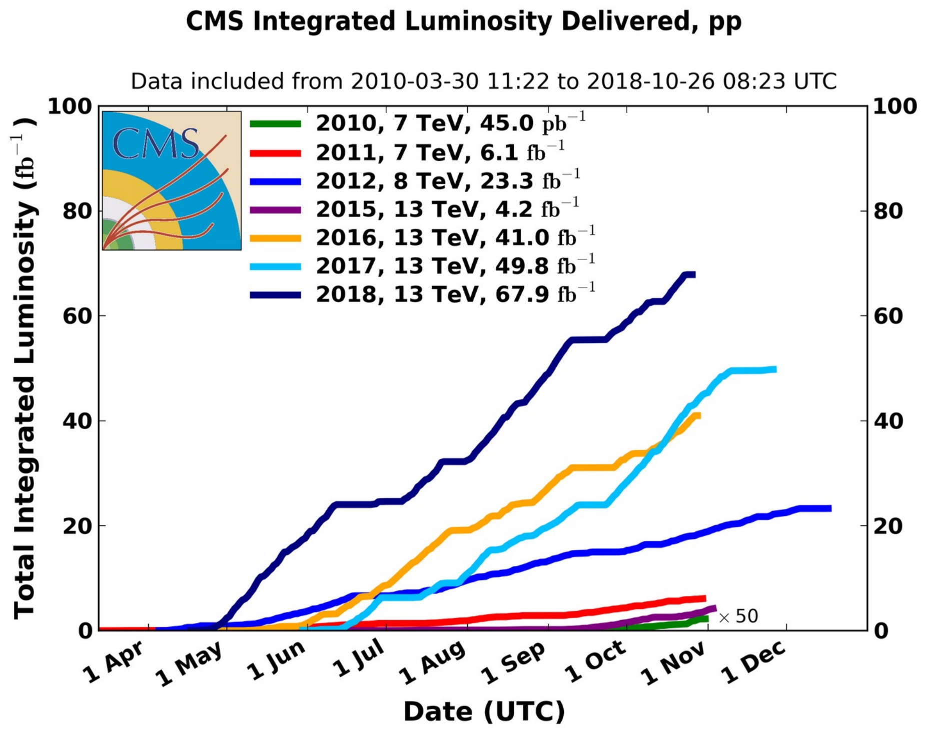
– β* is value of the beta function at the interaction point

can rewrite formula for the luminosity of an accelerator in terms of beam parameters :

$$\mathcal{L} = f \cdot n_b \cdot \frac{N_1 \cdot N_2}{4\pi\sqrt{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}$$

Luminosity: typical values

	peak $\mathcal{L}$ ($cm^{-2}\,s^{-1}$)	L_{in} (fb^{-1})
LEP II	$1 \cdot 10^{32}$	3
KEKB / Belle	$2 \cdot 10^{34}$	710
Tevatron Run-II	$4 \cdot 10^{32}$	12
LHC Run-I (2010–2012)	$7.7 \cdot 10^{33}$	25
LHC Run-II (since 2015)	$2 \cdot 10^{34}$	122



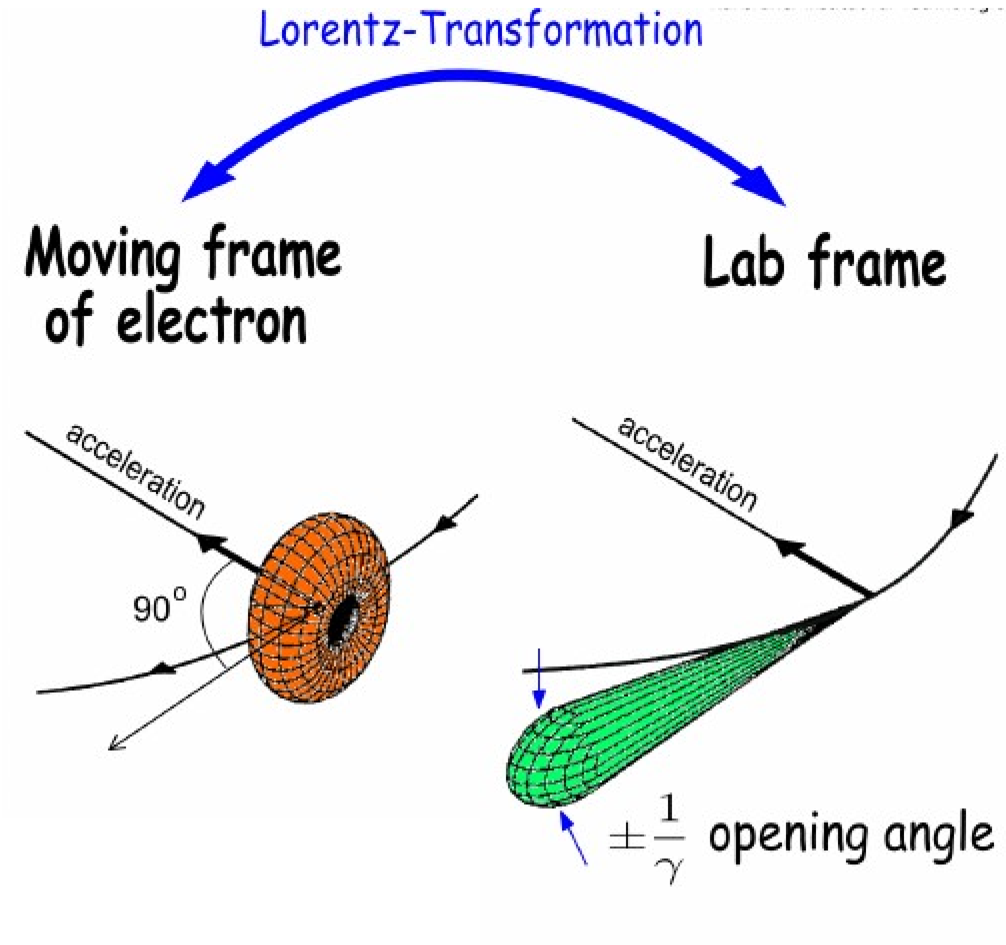
Synchrotron Radiation

QED: accelerated charges emit photons

→ particles kept on a circle in a synchrotron emit **"synchrotron radiation"**

– very desired effect in synchrotron light sources

– constant energy loss of beam particles
limits maximum energy of a circular electron accelerator !



desy.de

Energy loss per turn: $\Delta E = 2\pi \frac{R}{c} P$ scales with $\boldsymbol{R}^{-2}$ and $\boldsymbol{m}^{-4}$

- Electrons at LEP (100 GeV beam energy): $\Delta E \approx 3\,\mathrm{GeV}$
- Protons at LHC (6.5 TeV beam energy): $\Delta E \approx 2\,\mathrm{keV}$

Optical Resonances and Tune

Phase advance per turn: $\Delta\Psi = \Psi(s+L) - \Psi(s)$

Inserting in Hill's equation and integrating over one turn

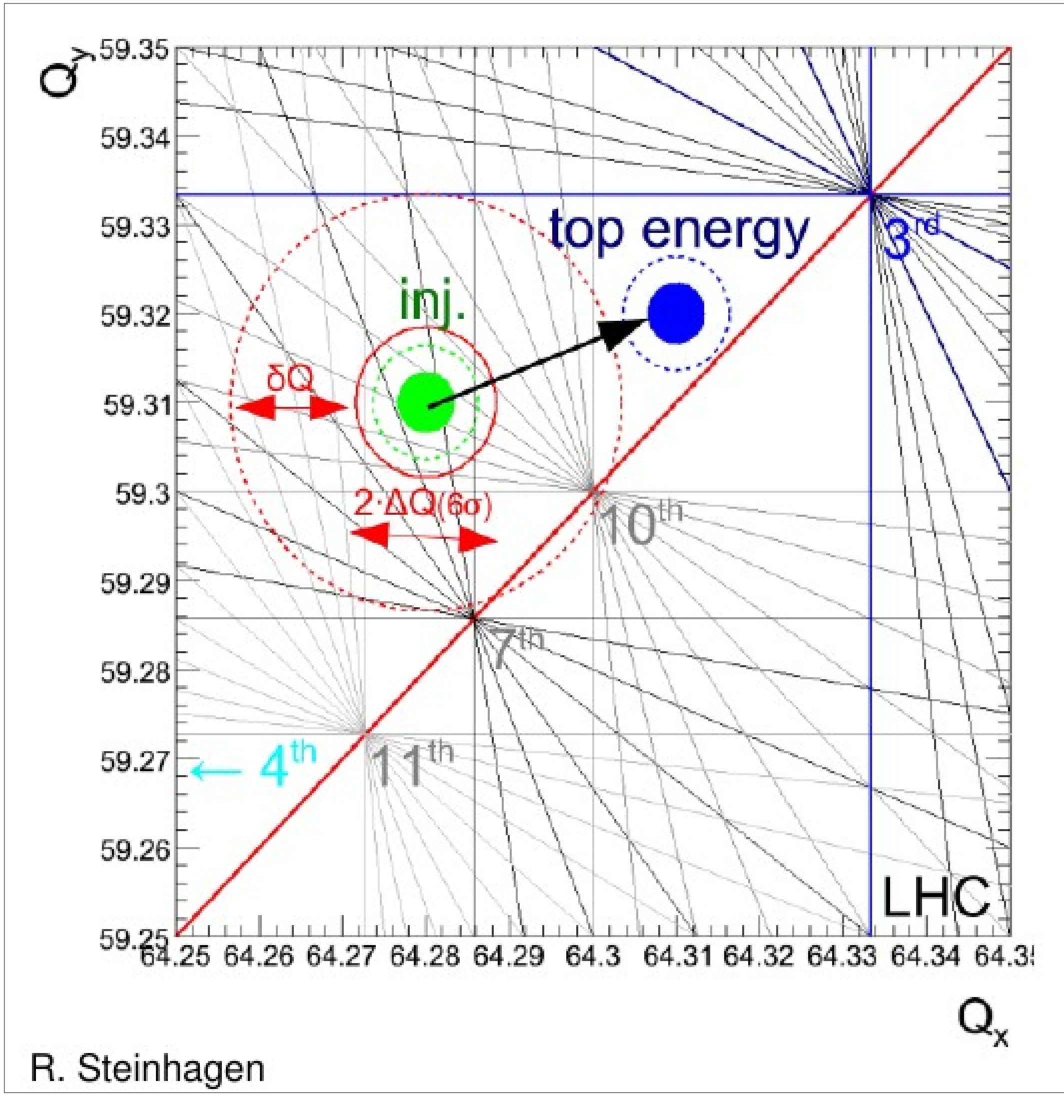
$\rightarrow$ "tune" $$Q = \frac{\Delta\Psi}{2\pi} = \frac{1}{2\pi}\oint \frac{ds}{\beta(s)}$$

tune is the number of oscillations per turn

- **betatron tune** $Q_{x,y}$
- analog: **synchroton tune** Q_s: number of logitudinal oscillations (or oscillations between max. and min. energy)

Danger: in case of integer tunes, m Q_x +n Q_y, perturbations hit beam particles always at the same phase;
$\rightarrow$ resonant build-up $\rightarrow$ beam loss !

Optical Resonances and Tune

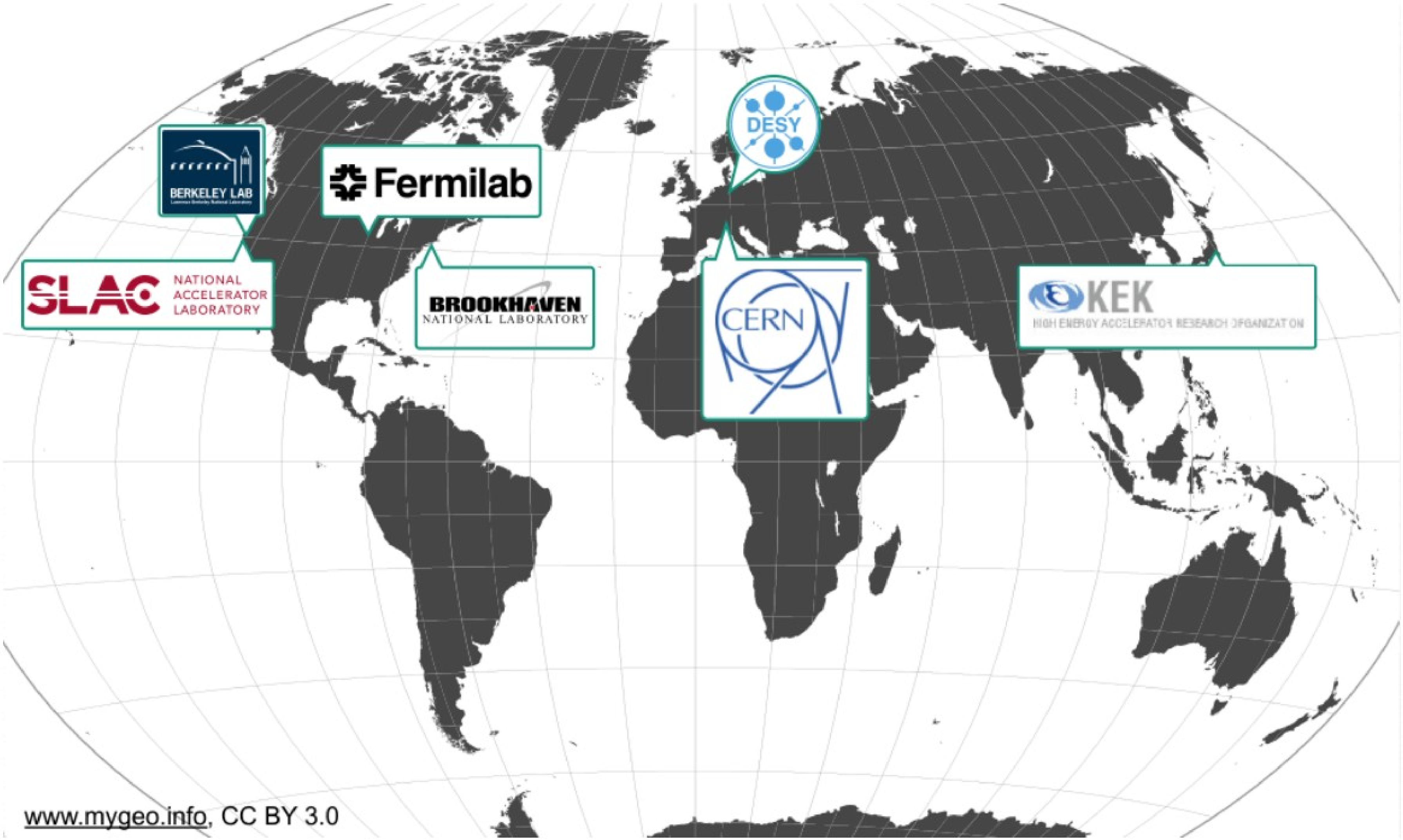


LHC "tune diagram" (Qx, Qy) with working points for injection (green dot), and for best collision performance (blue dot).

Tunes close to strong resonance lines (bold solid lines) must be avoided in order not to lose the beam.

World Map of Accelerators

Karlsruher Institut für Technologie



e^+e^- Colliders

Accelerator (Lab)	Operation	Type: Particles	Beam Energy (GeV)
LEP (CERN)	1989–2000	Storage ring: e^+e^-	45–104.6
SLC (SLAC)	1989–1998	Linear accelerator: e^+e^-	50
KEKB (KEK)	1999–2010	Storage ring: e^+e^-	e^-: 8.0, e^+: 3.5
PEP-II (SLAC)	1999–2008	Storage ring: e^+e^-	e^-: 9.0, e^+: 3.1
Super-KEKB (KEK)	since 2017	Storage ring: e^+e^-	e^-: 7.0, e^+: 4.0
ILC (Japan?)	?	Linear accelerator: e^+e^-	250–500
CEPC (China)	??	Storage ring: e^+e^-	120
CLIC (?)	???	Linear accelerator: e^+e^-	1500
FCC-ee (CERN)	???	Storage ring: e^+e^-	45–175

Further at lower energies: VEPP (Novosibirsk), BEPC (Bejing), DAΦNE (Frascati), CESR (Cornell)

pdg.lbl.gov

Hadron Colliders

Accelerator (Lab)	Operation	Type: Particles	Beam Energy (GeV)
HERA (DESY)	1992–2007	Storage ring: $e^{\pm}p$	$e^{\pm}$: 30, p: 920
Tevatron (Fermilab)	1987–2011	Storage ring: $p\bar{p}$	900–980
RHIC (BNL)	since 2000	Storage ring: pp, heavy ions	100/proton
LHC Run-I (CERN)	2009–2012	Storage ring: pp, heavy ions	2010/11: 3500 2012: 4000 (2510/proton)
LHC Run-II (CERN)	since 2015	Storage ring: pp, heavy ions	6500 (2760/proton)
HL-LHC (CERN)	2026–2035	Storage ring: pp, heavy ions	7000
FCC-hh (CERN)	???	Storage ring: pp	50 000

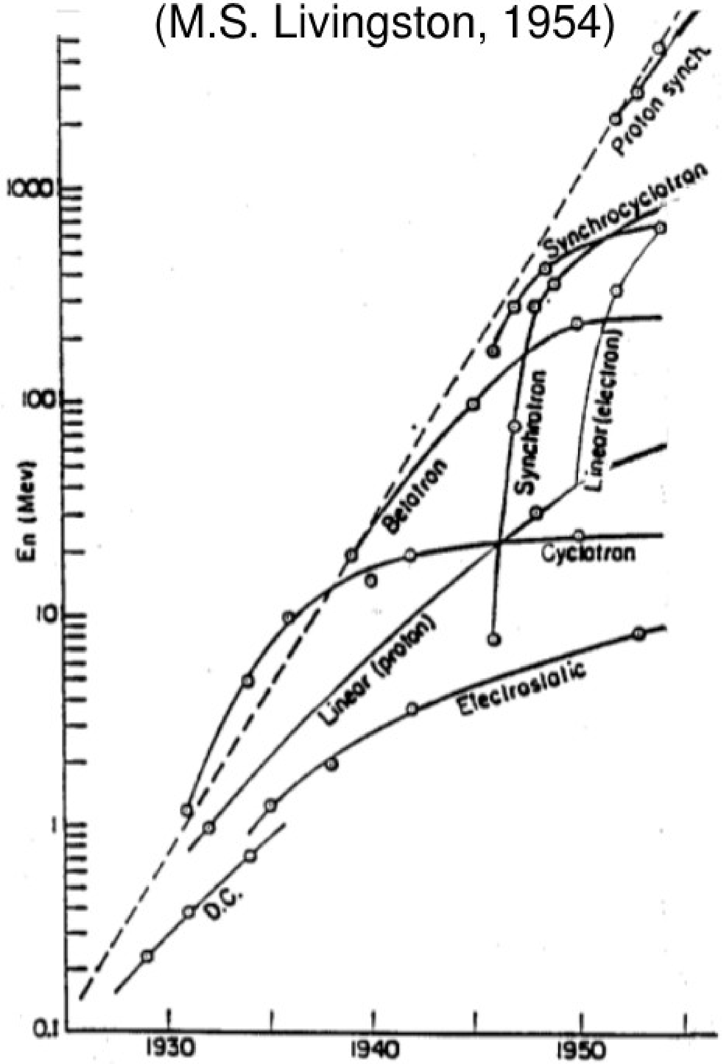
pdg.lbl.gov

Energy increase with time – "Livingston Plot"

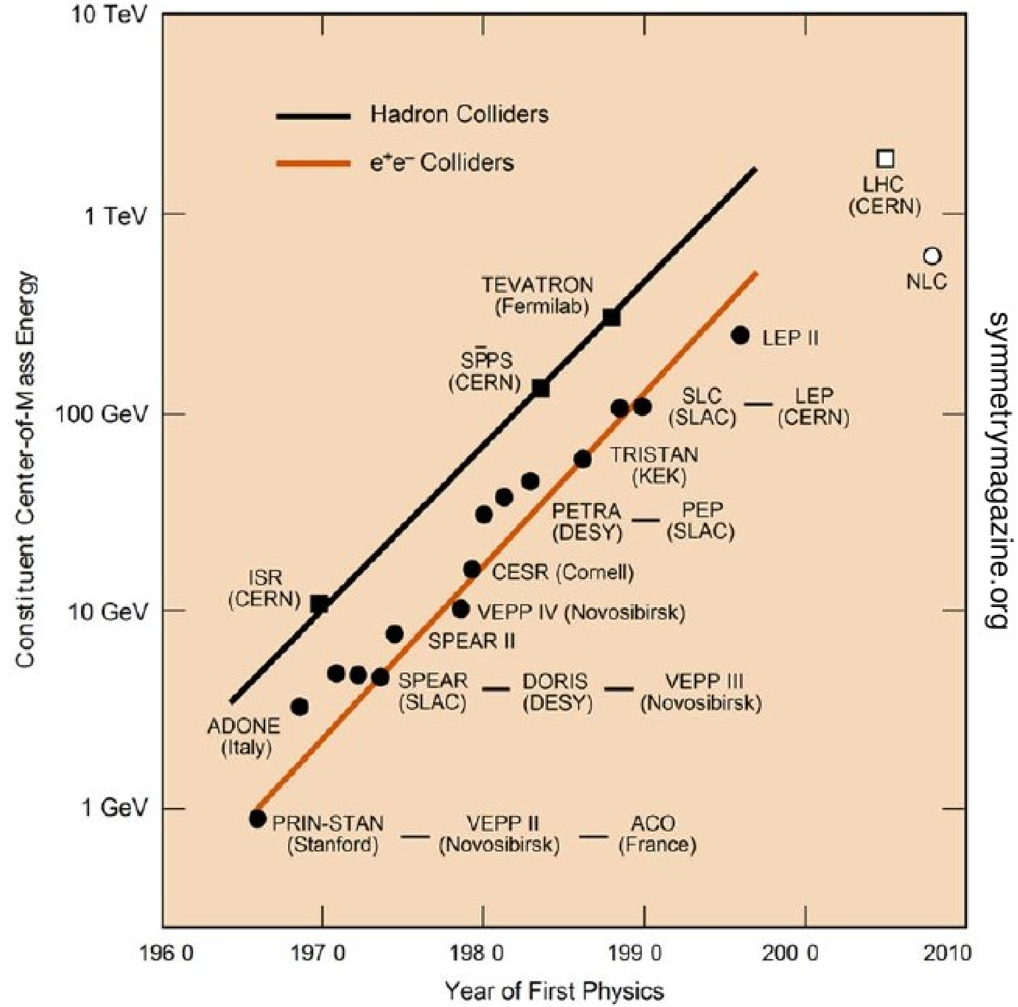
Empirically: doubling of energy every 6 years

original plot

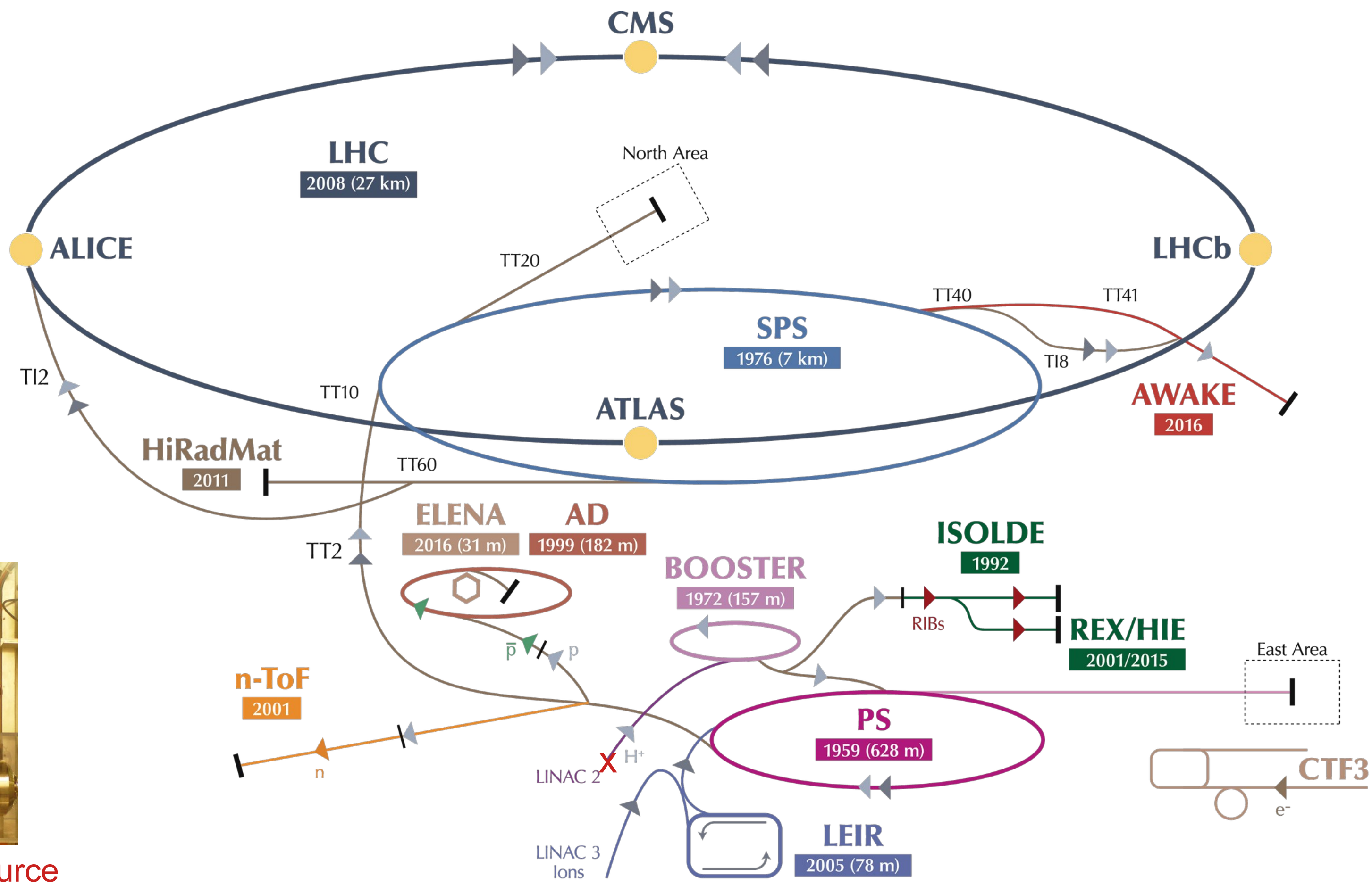
(M.S. Livingston, 1954)



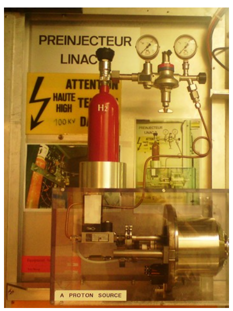
current plot



The CERN accelerator complex



http://cds.cern.ch



x LHC proton source

p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons) proton/antiproton conversion proton/RIB conversion

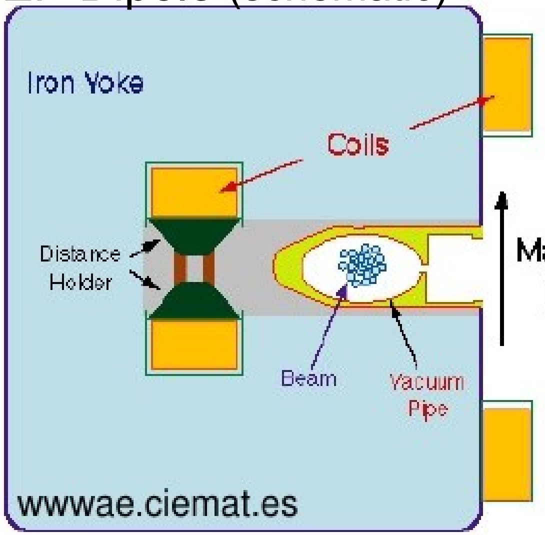
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

AWAKE Advanced WAKefield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

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

Magnet Technologies

LEP Dipole (schematic)

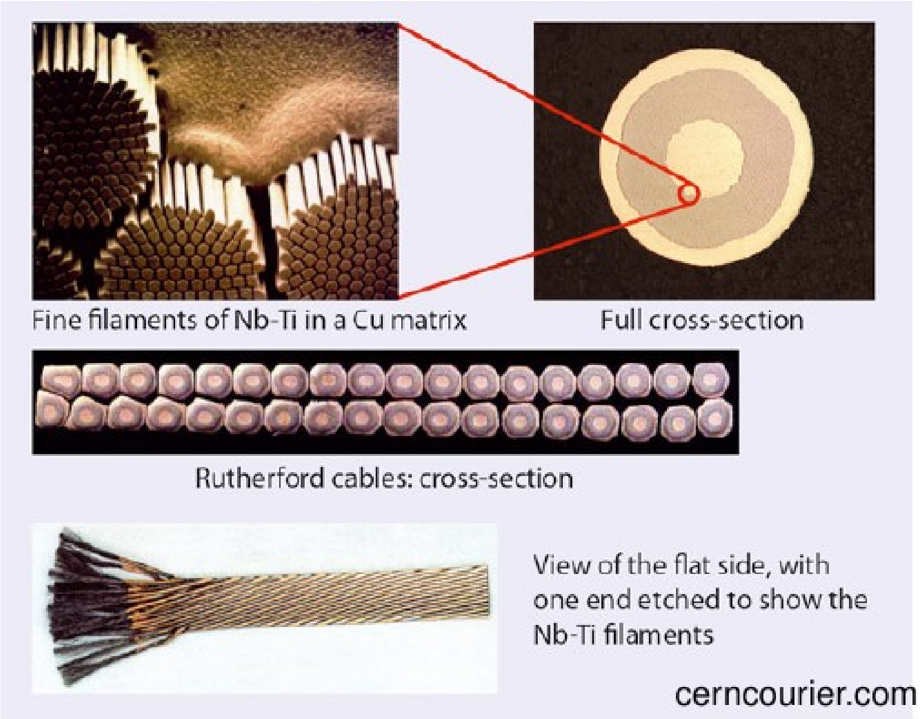


Normal conducting magnets

- Water-cooled copper coils with iron joke
- Limitation: ***magnetisation of iron saturates*** at $\rightarrow \boldsymbol{B \lesssim 2\,\mathrm{T}}$

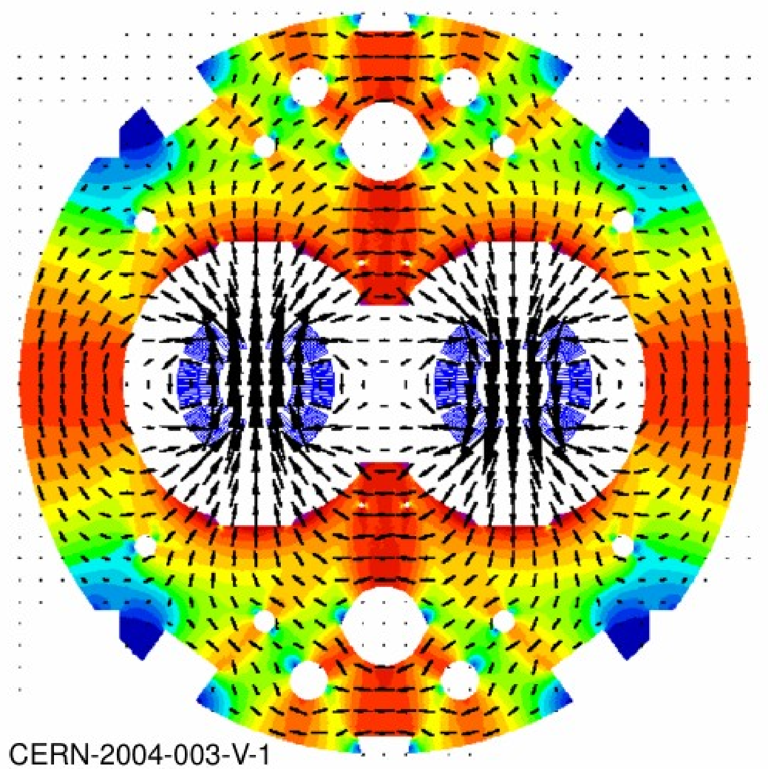
Superconducting magnets

- Charge only at surface: coils from NbTi filaments (7 µm) in copper matrix
- Operation below critical temperature: cooling with ***liquid Helium at 4 K*** (LHC: super-fluid He at 1.9 K)
- Limitation: collapse of super-conductivity at ***critical current*** ('quench') $\rightarrow \boldsymbol{B \lesssim 10\,\mathrm{T}}$ for NbTi

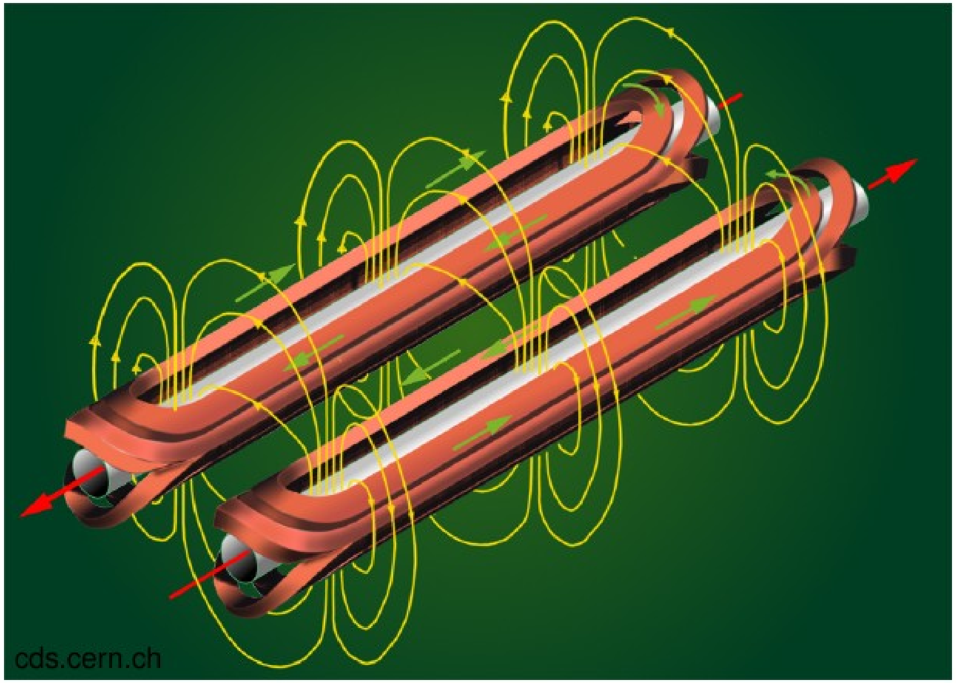


LHC Dipoles

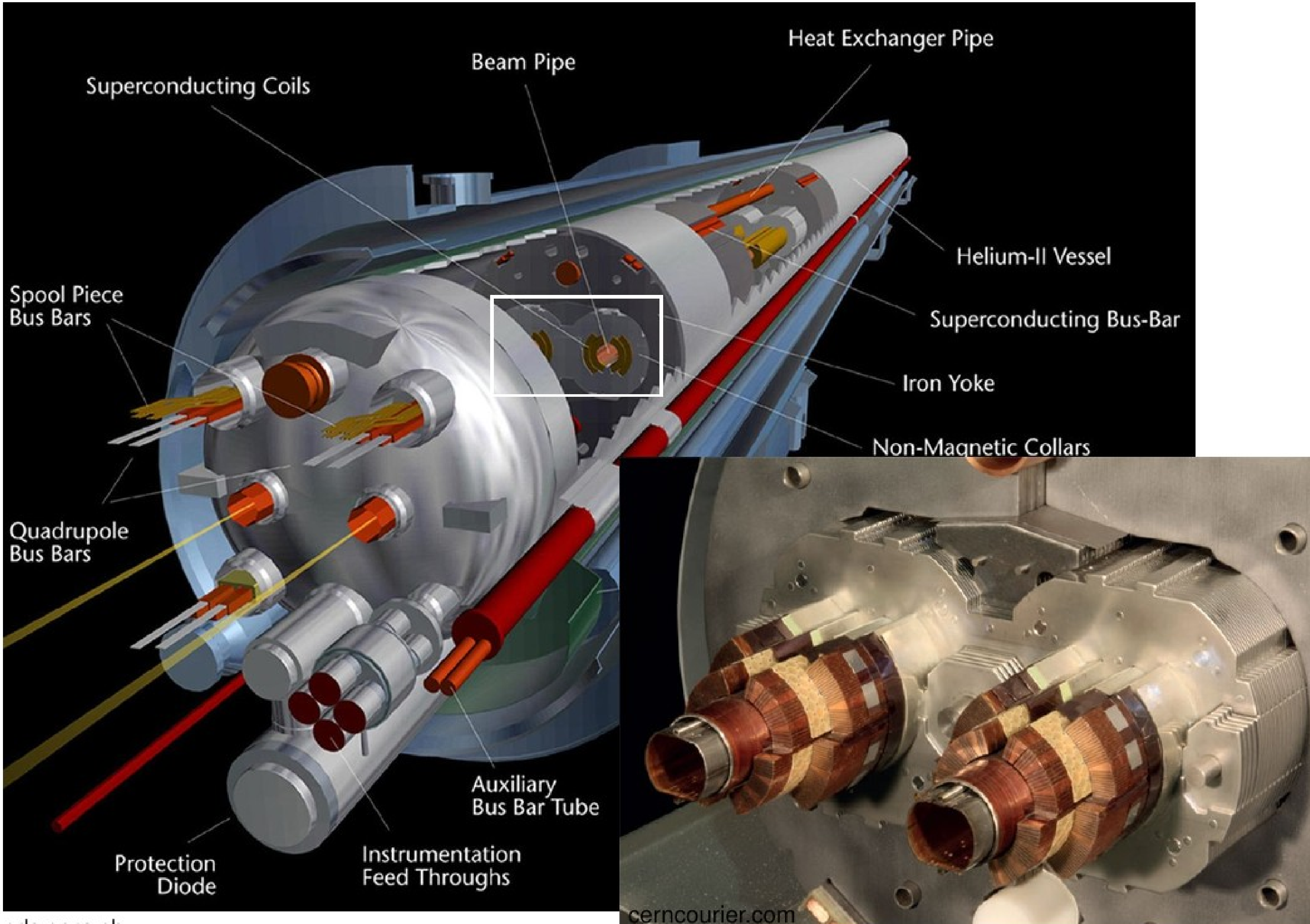
- Identical particles in each beam (e. g. *pp*) in opposite direction
  - Two beam pipes
  - Magnetic field lines in opposite direction



CERN-2004-003-V-1



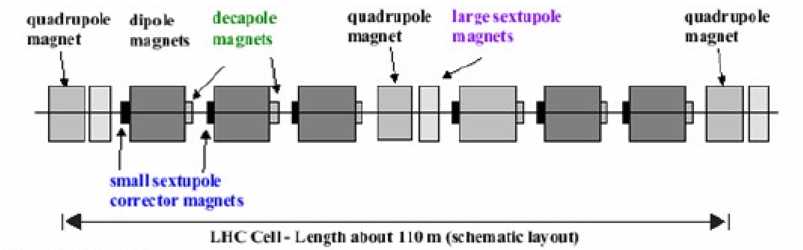
LHC Dipoles



cds.cern.ch

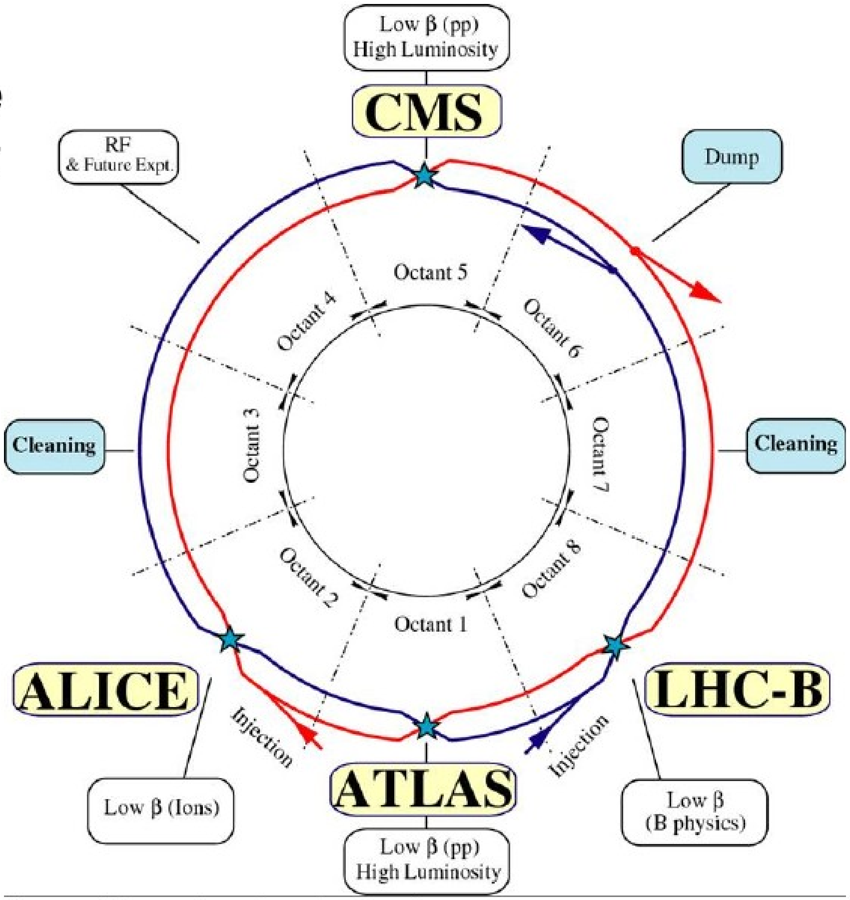
LHC Layout

- LHC: 8 arcs and 8 straight sections ('insertions')
- ***Arcs*** (2.45 km)
  - 23 arc 'cells' with FODO structure (main dipoles, quadrupoles, other multipoles)



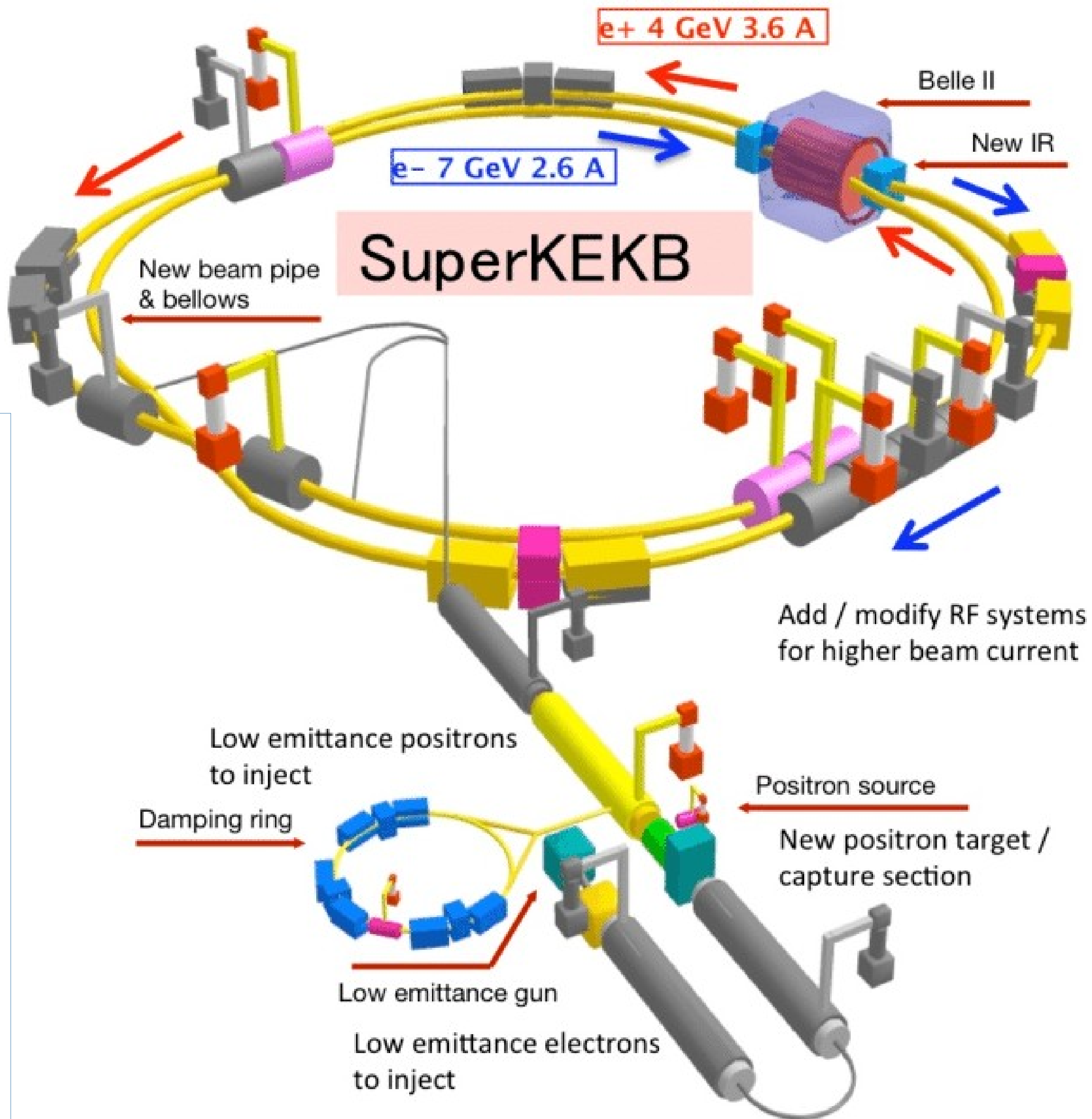
lhc-closer.es

- ***Straight Sections*** (528 m)
  - Experiments
  - Beam injection
  - RF acceleration
  - Beam dump
- Interaction points: "low-β triplets" with ***best-possible focusing***



lhc-machine-outreach.web.cern.ch

SuperKEKB acce – an asymmetric B factory



SuperKEKB is an upgrade of the former **KEKB** accelerator

– an example of an (asymmetric) electron-positron collider

- two rings, one for 4 GeV positrons and one for 7 GeV electrons
- centre-of-mass system at $\Upsilon(4s)$ resonance is boosted to increase resolution on displaced vertices from B hadron decays
- aiming at a luminosity of 8 x 10^{35} cm^{-1} s^{-1}

Future accelerators

Future Accelerators

Discovery of new phenomena is possible via two roads:

1. higher energy to directly produce new particles

   Requires accelerators with higher energy and/or higher luminosity

   – luminosity increase of the LHC (High-Luminosity LHC, approved)

   – an new proton accelerator with a tunnel of 80 – 100km length

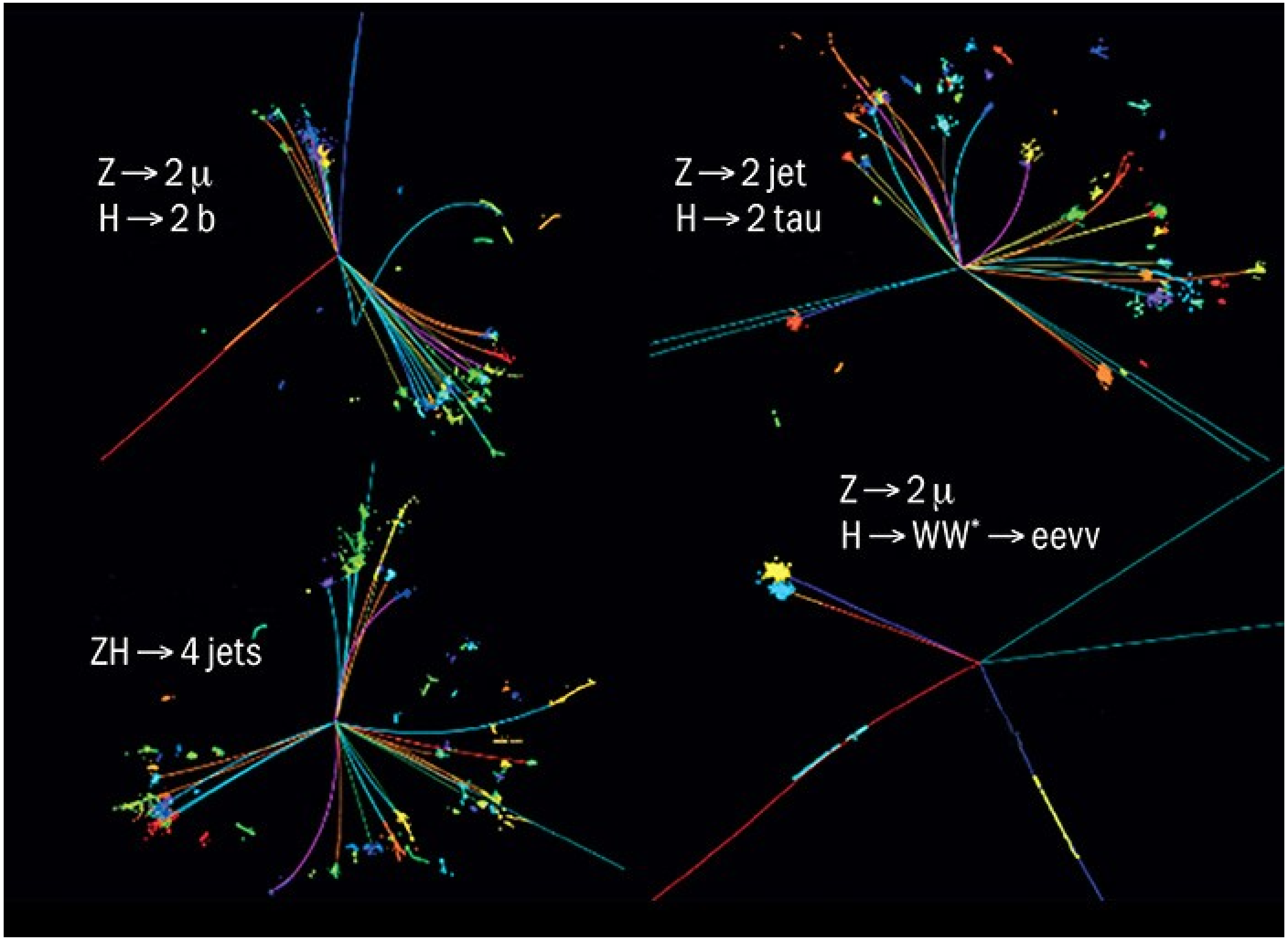
2. higher precision of measurements

   Requires better control of initial conditions and a “clean” environment

   – electron-positron collisions at energies of 500 GeV – 1 TeV
   losses due to synchrotron radiation require either
   – a very large ring or
   – a linear collider

   – a myon collider (?) very challenging

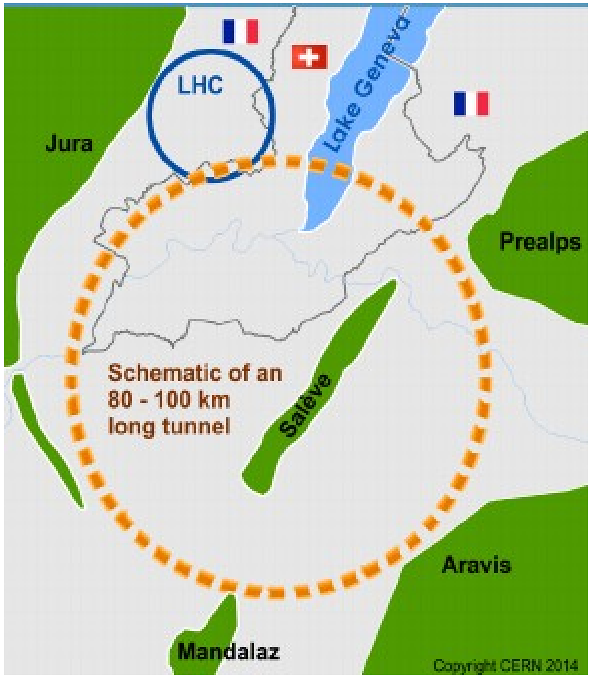
Higgs Signatures in e+e-

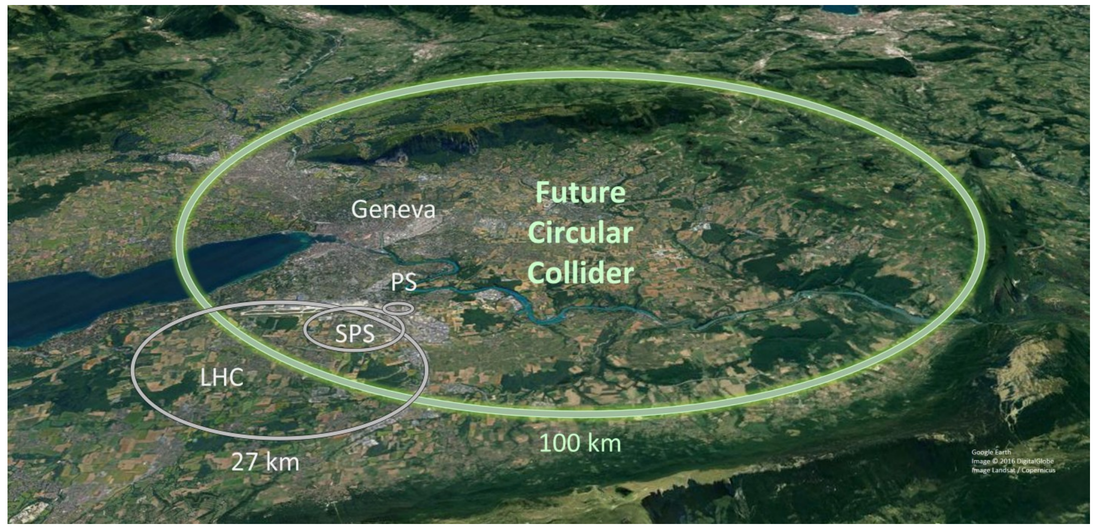


CERN courier, June 2018

Simulated Higgs-boson signals with different decay final states for 240 GeV electron–positron collisions envisaged at CEPC, using a PFA-oriented detector design. Image credit: IHEP

Ideas for a Future Circular Collider @ CERN





https://home.cern/science/accelerators/future-circular-collider

Large radius needed to keep particles in the ring:

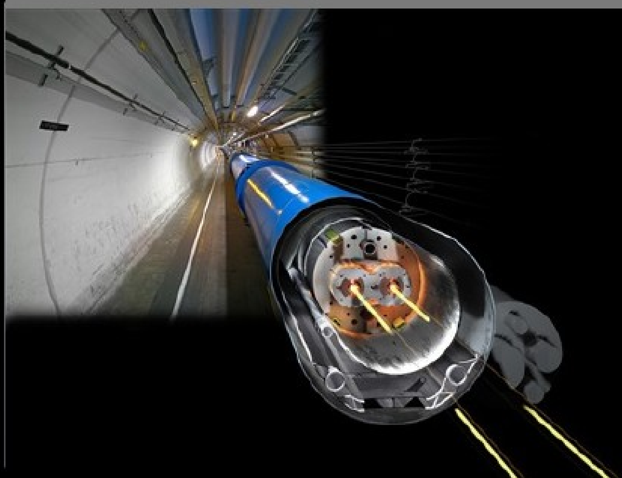
$$\rho\,[\mathrm{m}] = 3.336\,\frac{p\,[\mathrm{GeV/c}]}{B\,[\mathrm{T}]}$$

Options:

- electron – positron collisions @ 90 – 350 GeV (Z and Higgs Factory)
- hadron – hadron collisions @ ~100 TeV
- electron/positron – hadron collisions (?)

FCC: technological challenges

LHC: 1232 dipoles with 8 T



https://cds.cern.ch; CERN-AC-1107167-02

KIT Roebel cables & magnet for HL-LHC

600 A MgB2 Kabel

https://cds.cern.ch

FCC needs 4 x more dipole magnets with twice the field of the LHC

High temperature superconductors for even higher beam energies and as an option for power distribution

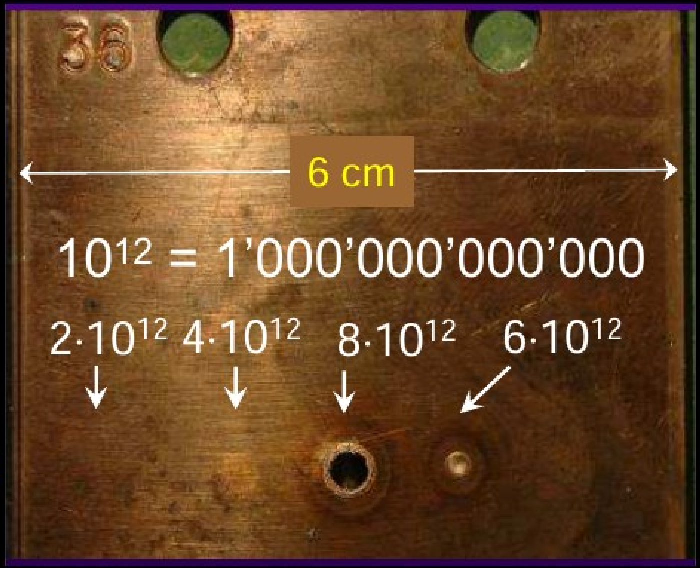
FCC: more challenges

- Energy in the LHC
  - Magnets: 10 GJ

≙ Airbus A380 mit 700 km/h

  - Beam: 362 MJ

≙ 120 kg TNT oder 20 kg Schweizer Käse

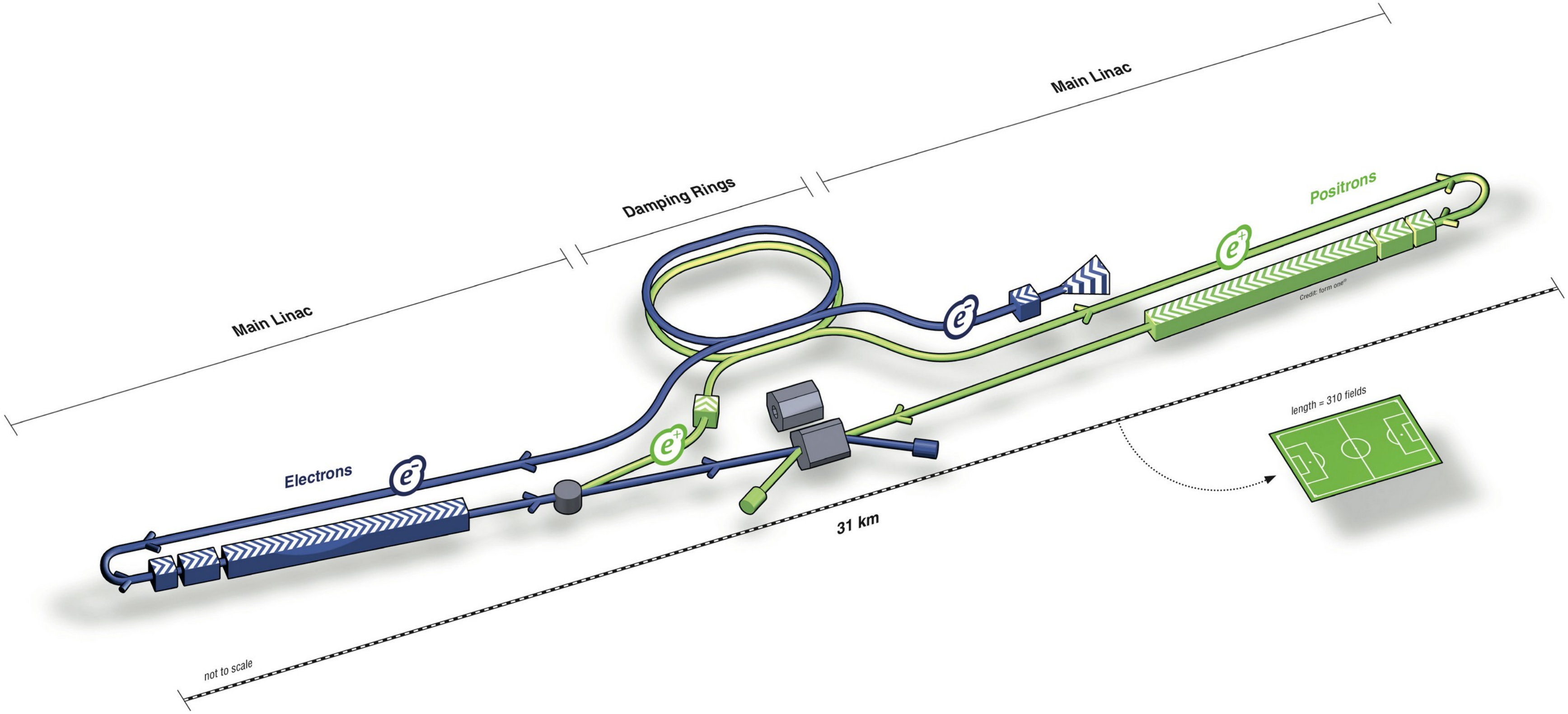


CERN protons at 450 GeV

V. Kain, H. Burkhardt, CERN

Anke-Susanne Müller, GK workshop 2019

The International Linear Collider (ILC)



https://ilchome.web.cern.ch/

a “mature” concept:

– superconducting cavities already in use at DESY (European XFEL)

– technical design report exists

– experimental collaborations and detector proposals exist

possible place: Japan, but decision differed in March 2019

CLIC (CERN Linear Collider) @ 3 TeV

A novel concept for particle acceleration:

Cavities driven by a particle beam

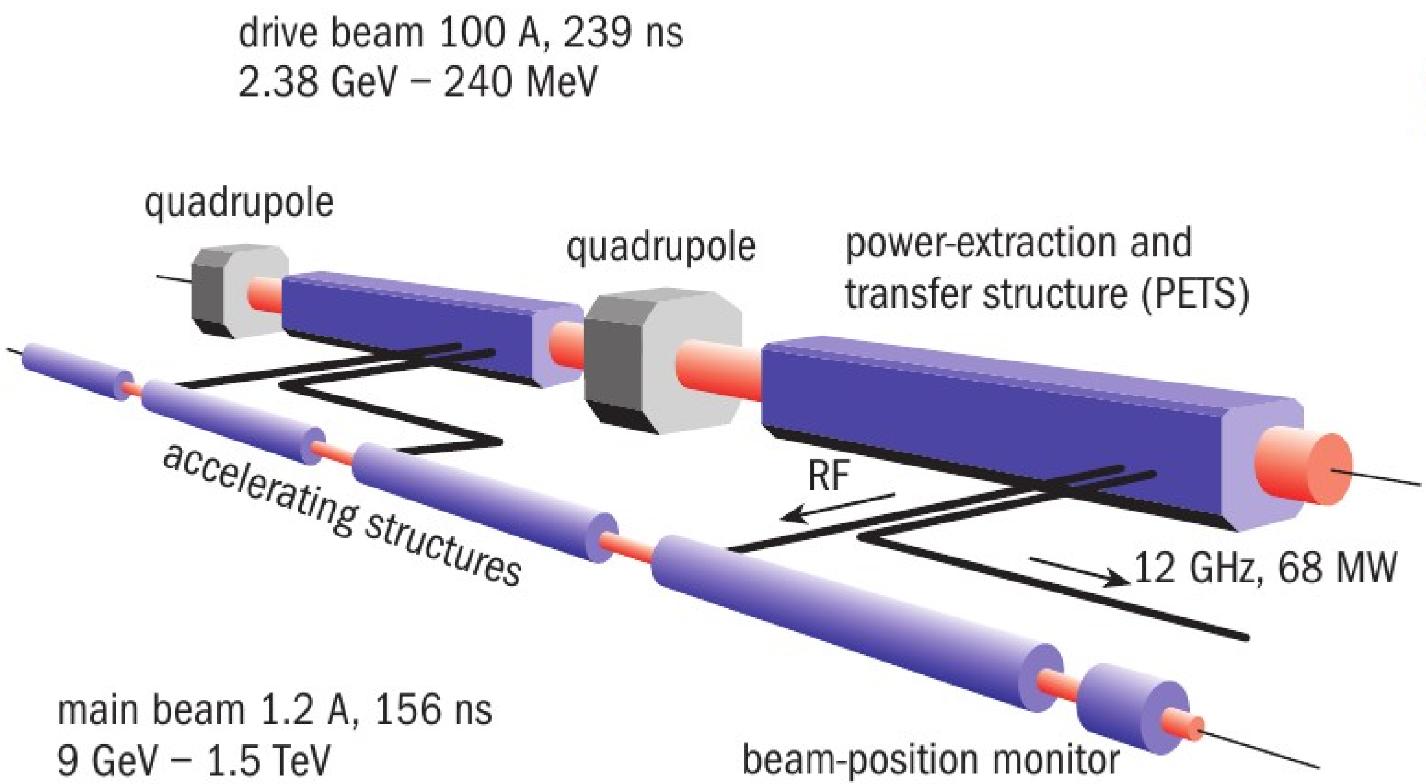
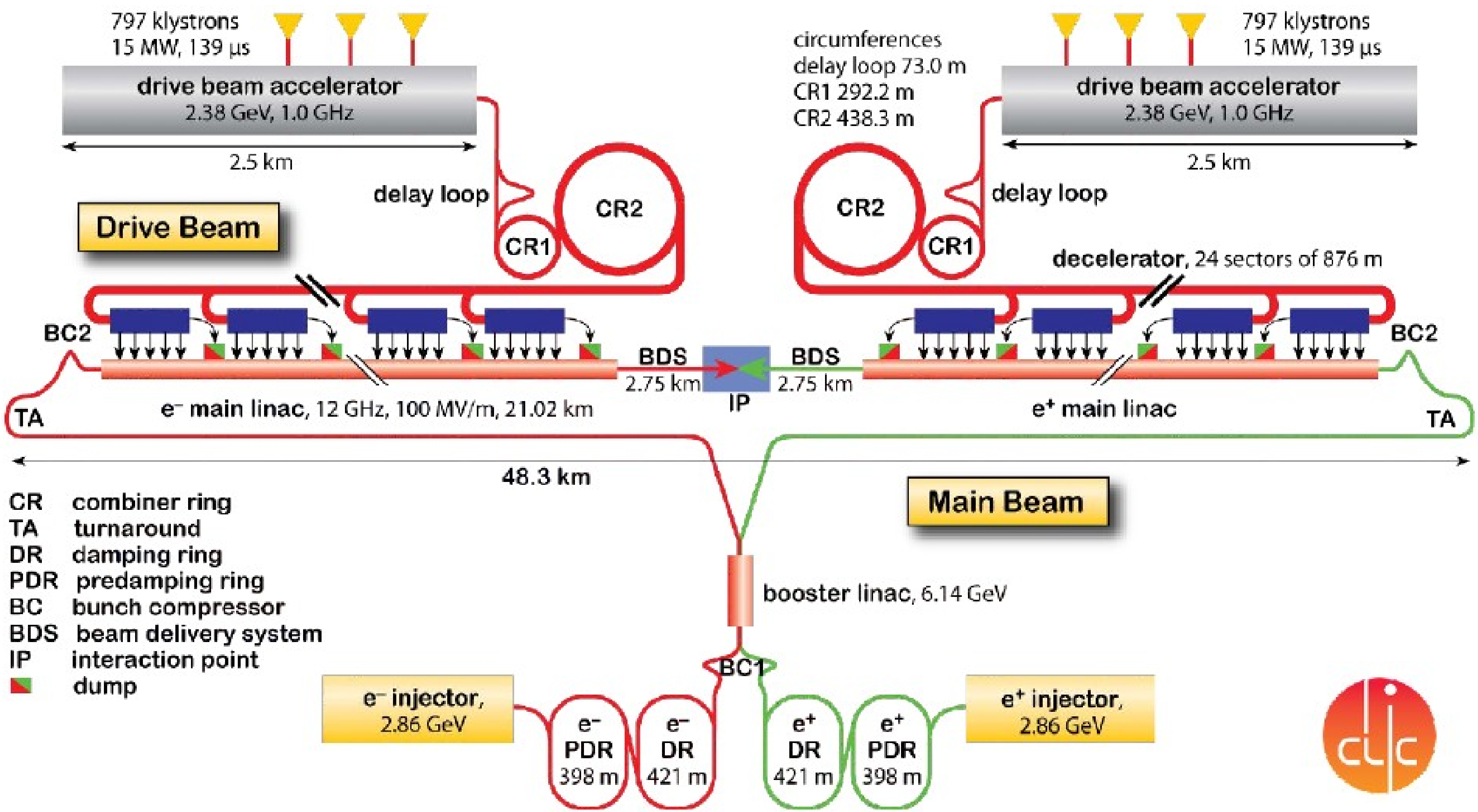


Fig. 2.6: Principle of the two-beam scheme: The beam power in the Drive Beam is converted to RF power in PETS, each feeding two accelerating structures in the Main Beam running parallel at a distance of 60 cm.

CLIC CONCEPTUAL DESIGN REPORT, CERN-2012-007

CLIC (CERN Linear Collider) @ 3 TeV



CLIC CONCEPTUAL DESIGN REPORT, CERN-2012-007

A new Accelerator Complex in China ?

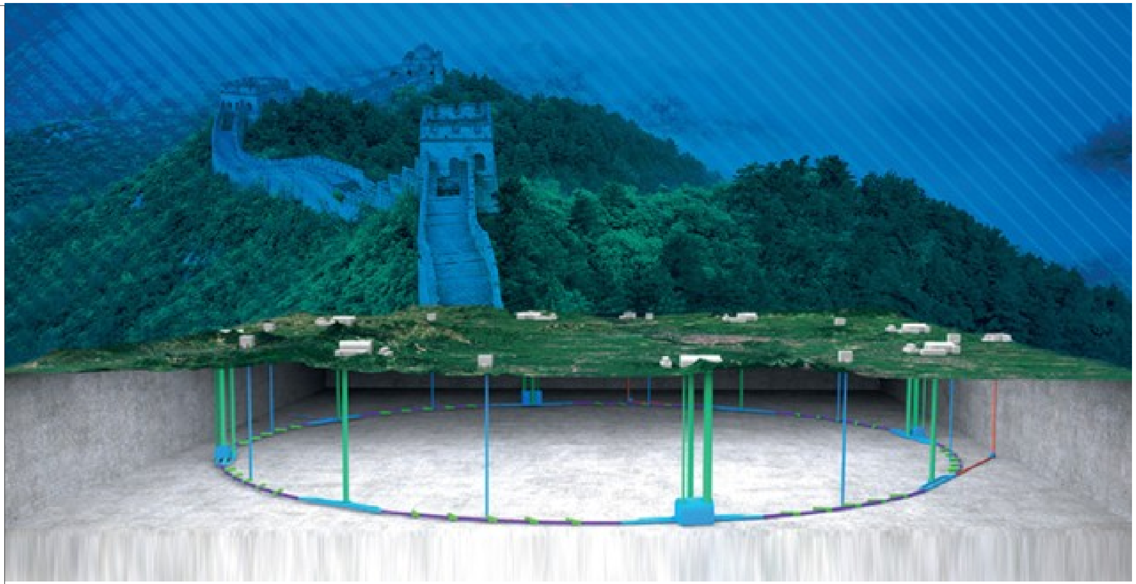
China's bid for

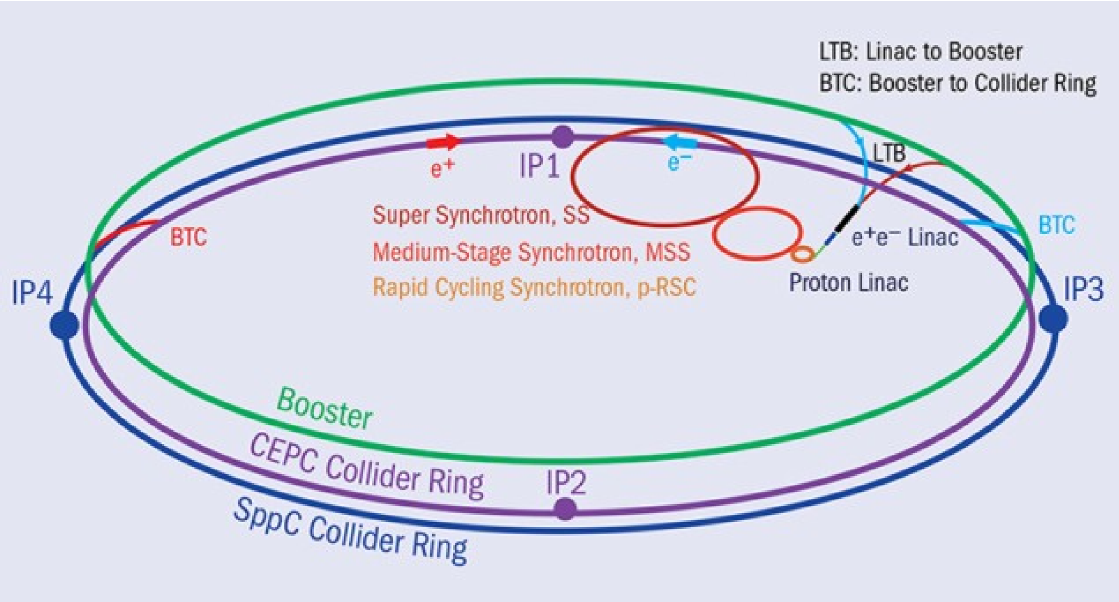
a circular electron– positron collider

and – later –

a proton-proton machine

in a ~100 km tunnel





CERN courier, June 2018

Several sites in China under study for a possible 100 km-circumference collider

New concepts for acceleration

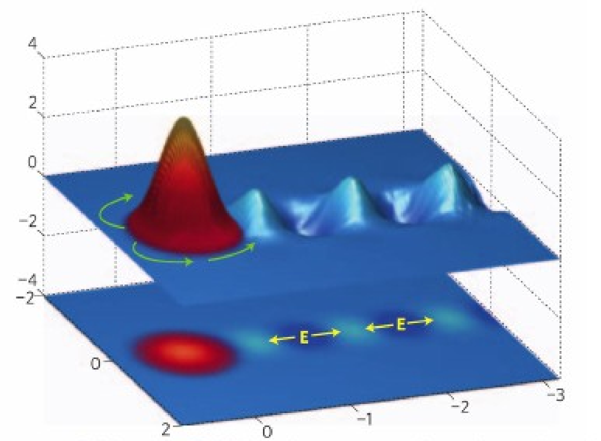
Laser Wake Field Accelleration in a plasma

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

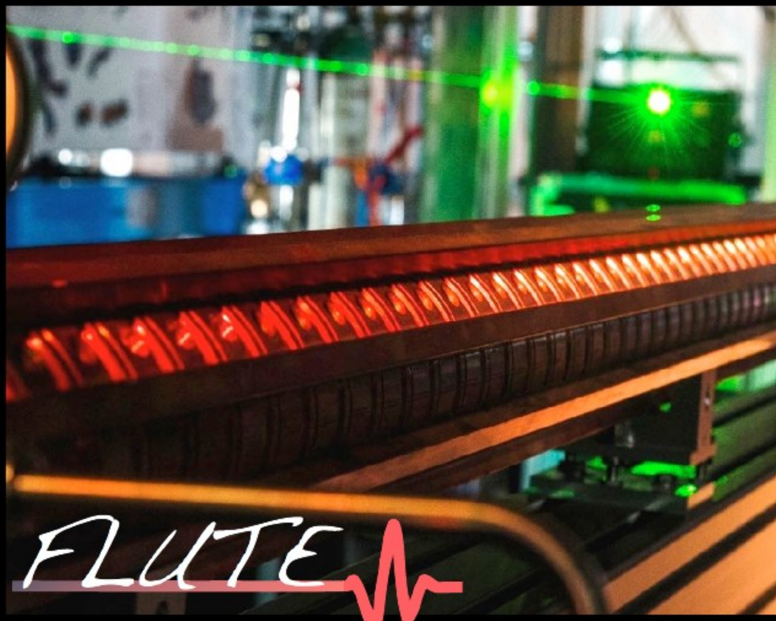


Bildquelle: S.M. Hooker, nature photonics 7 (2013)

Courtesy Axel Bernhard

- Laser pulse generates plasma wave by ponderomotive force $\propto \nabla I(r)$
- Charge separation → longitudinal electric fields
- Acceleration gradients of GeV cm^{-1} are achieved

Activities @ KIT



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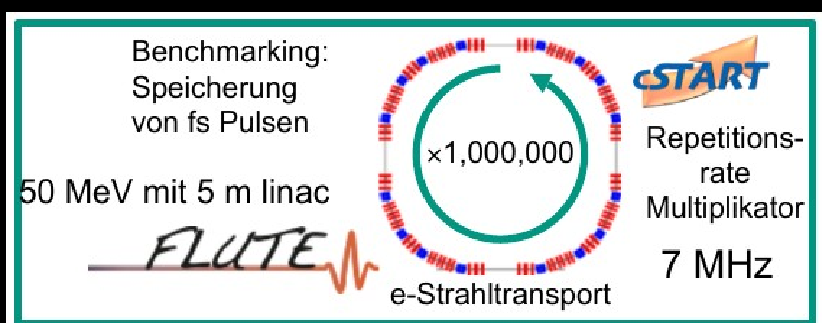

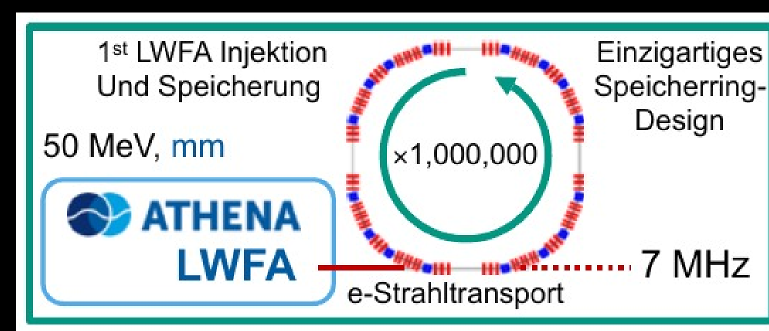

Contact: Prof. Dr. Anke-Susanne Müller