3. Particle accelerators

3.1 Relativistic particles

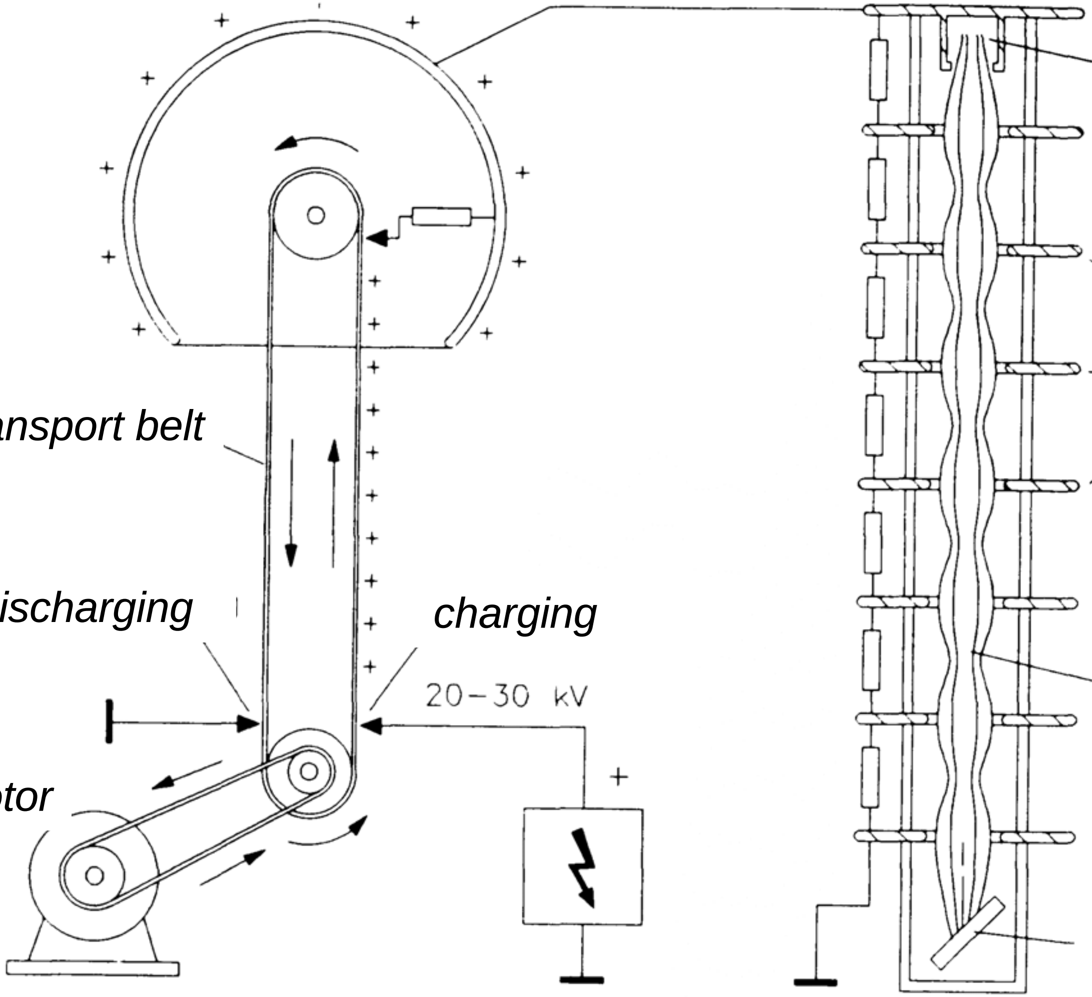
3.2 Electrostatic accelerators

3.3 Ring accelerators
Betatron // Cyclotron // Synchrotron

3.4 Linear accelerators

3.5 Collider

Van-de-Graaf accelerator



transport belt

discharging

charging

motor

particle source

accelerating electrodes

beam

target

$E = ZeU$

E_{max}=15 MeV/nucleon

Particle Current=100 μA

Tandem-accelerator

(Povh et al., N & P)

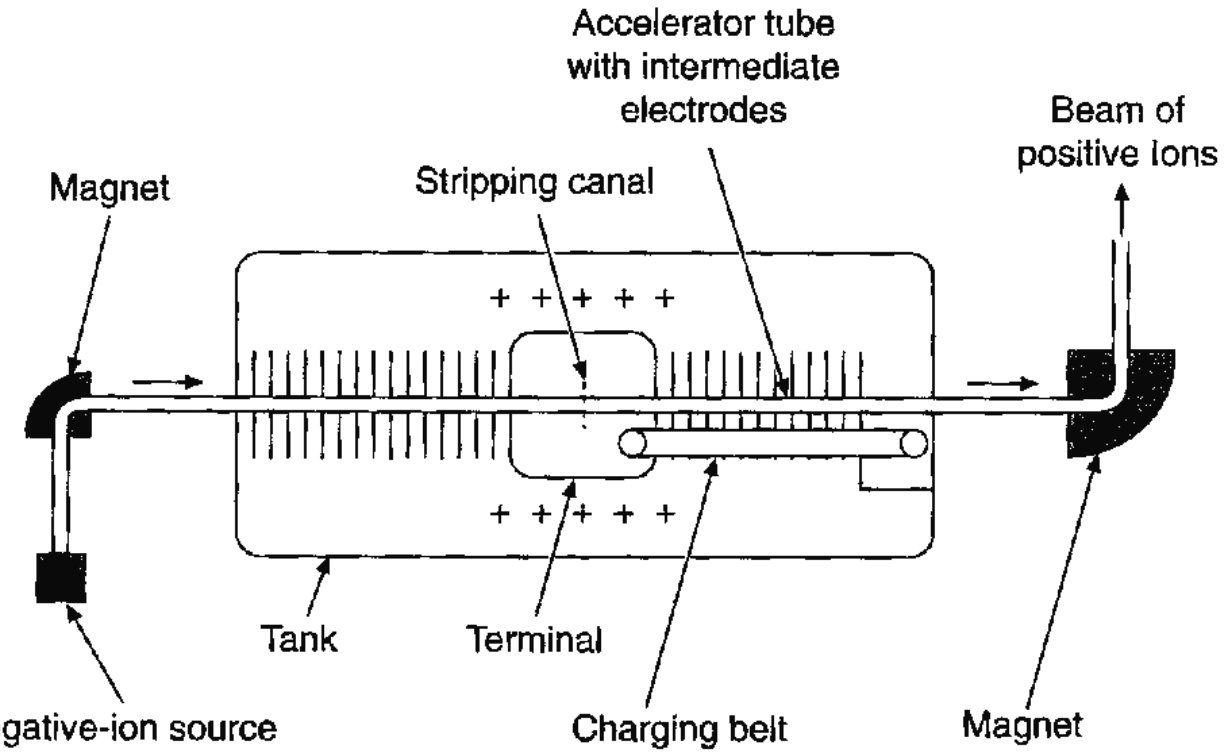


Fig. A.1. Sketch of a tandem Van de Graaff accelerator. Negative ions are accelerated from the left towards the terminal where some of their electrons are stripped off and they become positively charged. This causes them to now be accelerated away from the terminal and the potential difference between the terminal and the tank is traversed for a second time.

RING ACCELERATORS

1) The Betatron

$q\mathbf{v} \times \mathbf{B}_0 = -m\mathbf{v} \times \omega$

ω_C Cyclotron Frequency such that: $q\mathbf{B}_0 = -m w_c = -m\, v/\mathbf{r} = -|\mathbf{p}|/r$

If we have a time dependent **B** field, this induces an electric field that can be used for accelaration.

$$\nabla \times E = -\frac{\partial B}{\partial t}, \quad Stoke\ Theorem:$$

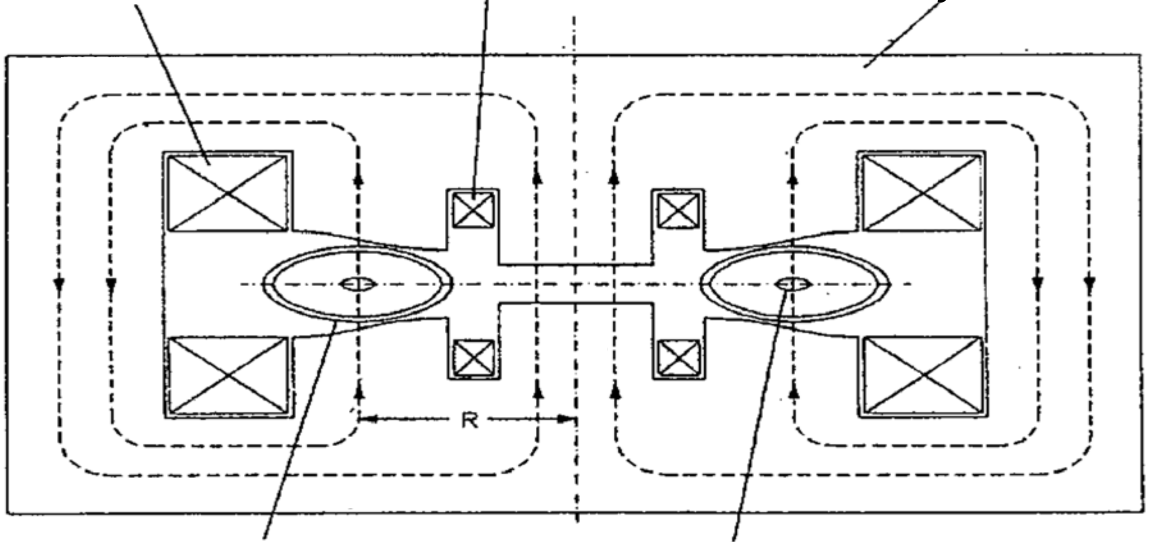
$$\Rightarrow 2\pi r E = -\frac{d}{dt}\left(\overline{B}\pi r^2\right), \quad r = r_0 \rightarrow F = \frac{d|p|}{dt} = qE = -\frac{q r_0}{2}\frac{d\overline{B}}{dt}$$

$$\Rightarrow \Delta|p| = -\frac{q r_0}{2}\Delta\overline{B} \quad and \quad \Delta|p| = -q r_0 \Delta B_0$$

$$\Rightarrow \Delta\overline{B} = 2\Delta B_0$$

The particle can be accellarated only once until the field reaches ist maximum value B_0

How it looks like:



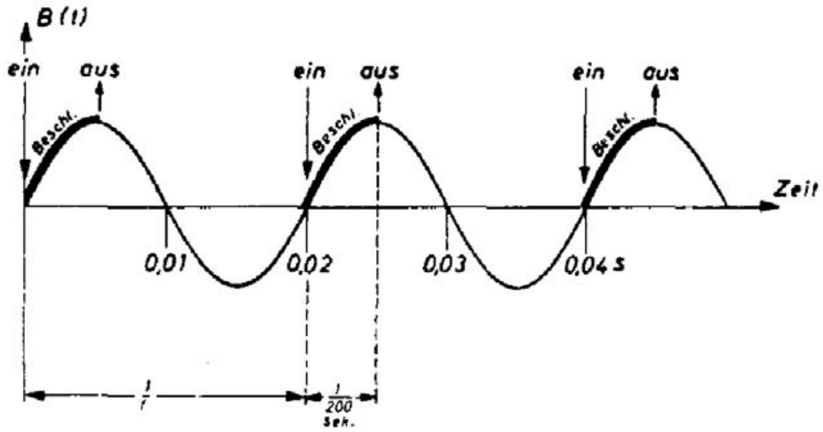
field coils

correction coils

iron yoke

vacuum chamber

beam



Axial stability

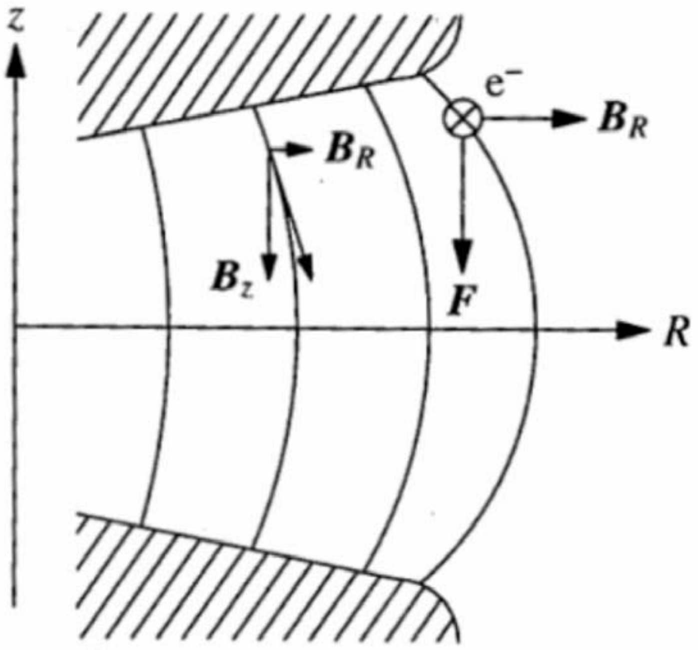


Abb. 2.10: Axiale Stabilitätsbedingung

The magnetic field forces the particle back to the medium plane.

The restoring force is provived by the magnetic field gradient.

E_{max}=300 MeV for e^-

2) Cyclotron

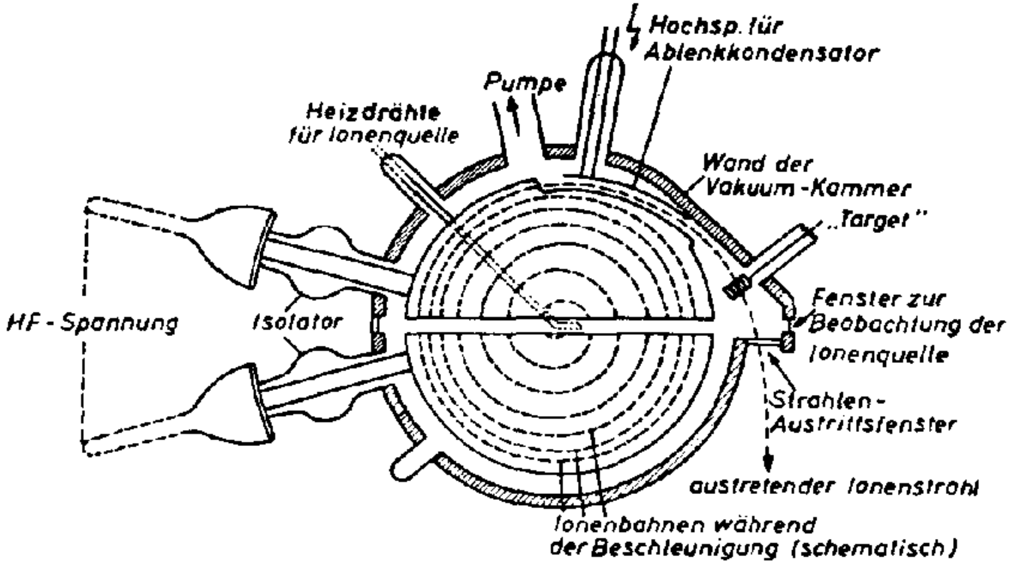
Constant Magnetic Field, Accelaration happens via a oscillating electric field between the dees
$\omega_{HF}=|\omega_Z|$ angular velocity of the particle (10 MHz)

$$m \cdot \frac{v^2}{r} = q \cdot (v \times B) \rightarrow \frac{v}{r} = \omega_Z = \frac{q}{m} B$$

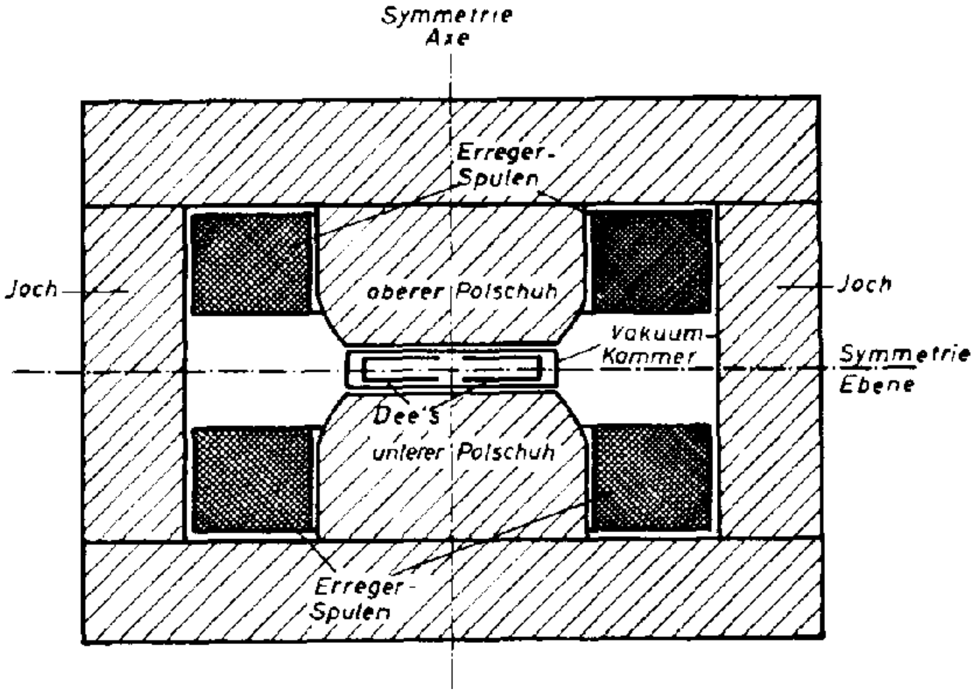
- Independent of the radius!!!
- Maximal Energy does not depend on E!!

$E_{MAX\ proton}$ =20 MeV

Schematic from the top



Side View



When the particles become relativistic m-->mγ with

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

Hence the particle becomes heavier and the ω_C diminishes.

One can overcome this problem reducing the HF frequency while the particle travels (**Syncrocyclotron,** only possible in bunch mode) or one can increase the magnetic field such that the radius stays constant

(**Isocyclotron,**possible in continuous mode)

$$\omega_Z = \frac{q}{m(E)} B(r(E))$$

Not suited for the accelaration of electrons!

One of the first Cyclotrons...

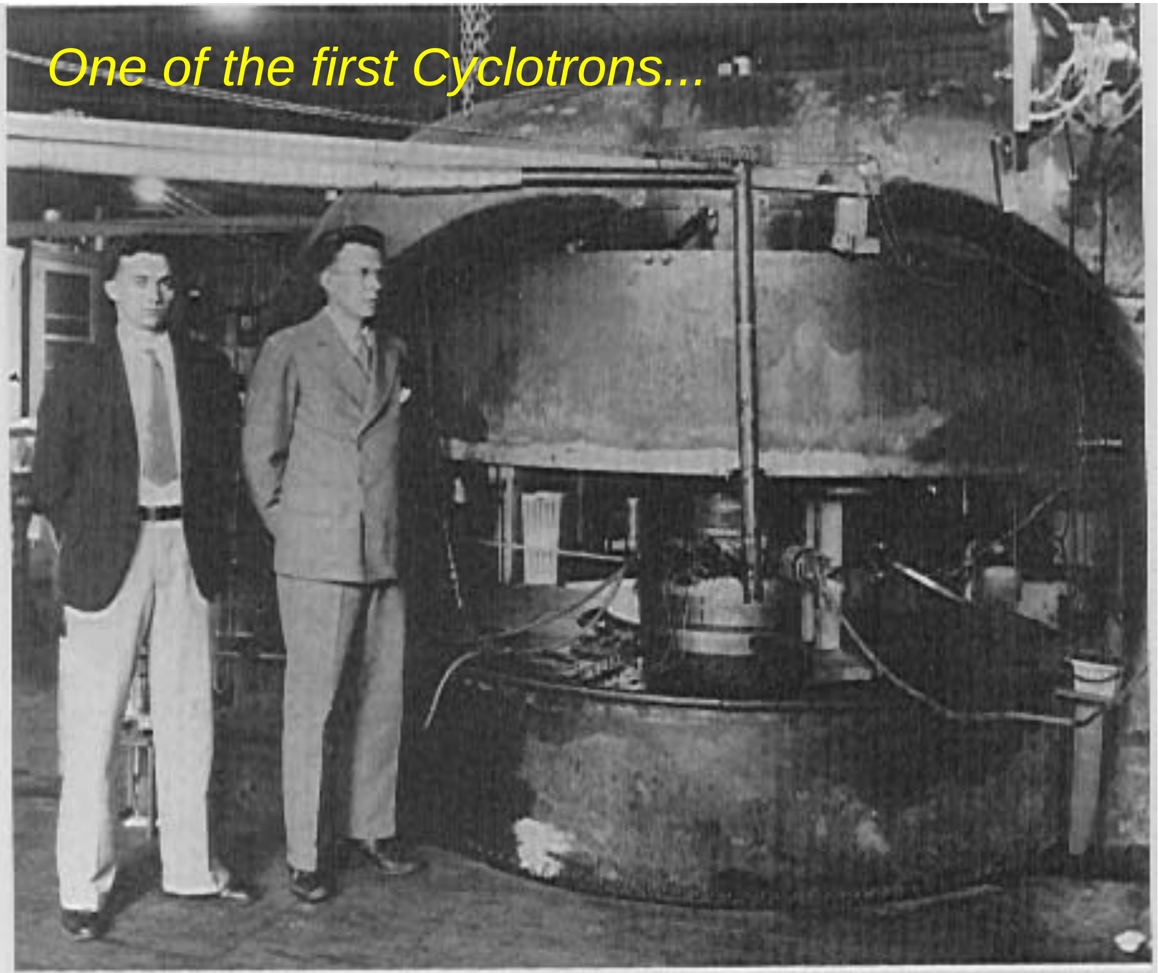


Abb. 11.7 **M. S. Livingston und E. O. Lawrence im ersten Strahlenlabor der *University of California* in Berkeley neben dem 37-inch-Zyklotron. Ursprünglich maß das Zyklotron 27 inch, es wurde aber auf 37 inch vergrößert und zur Messung des magnetischen Moments von Neutronen sowie zur Herstellung des ersten künstlichen Elements, Technetium, eingesetzt. (Lawrence Berkeley Laboratory)**

... and a little bit later

Abb. 11.9 **Das nach dem Krieg gebaute 184-inch-Synchrozyklotron mit einem Teil der an seinem Bau beteiligten Belegschaft. Mit dieser Maschine wurden die ersten künstlichen Mesonen erzeugt. (Lawrence Berkeley Laboratory)**

The isochrone- cyclotron at PSI

Synchrotron

For relativistic particles (v≈c):

$$\frac{v}{r} = \frac{q}{m} B \rightarrow r = \frac{mv}{qB} = \frac{p}{qB} \approx \frac{E}{qcB}$$

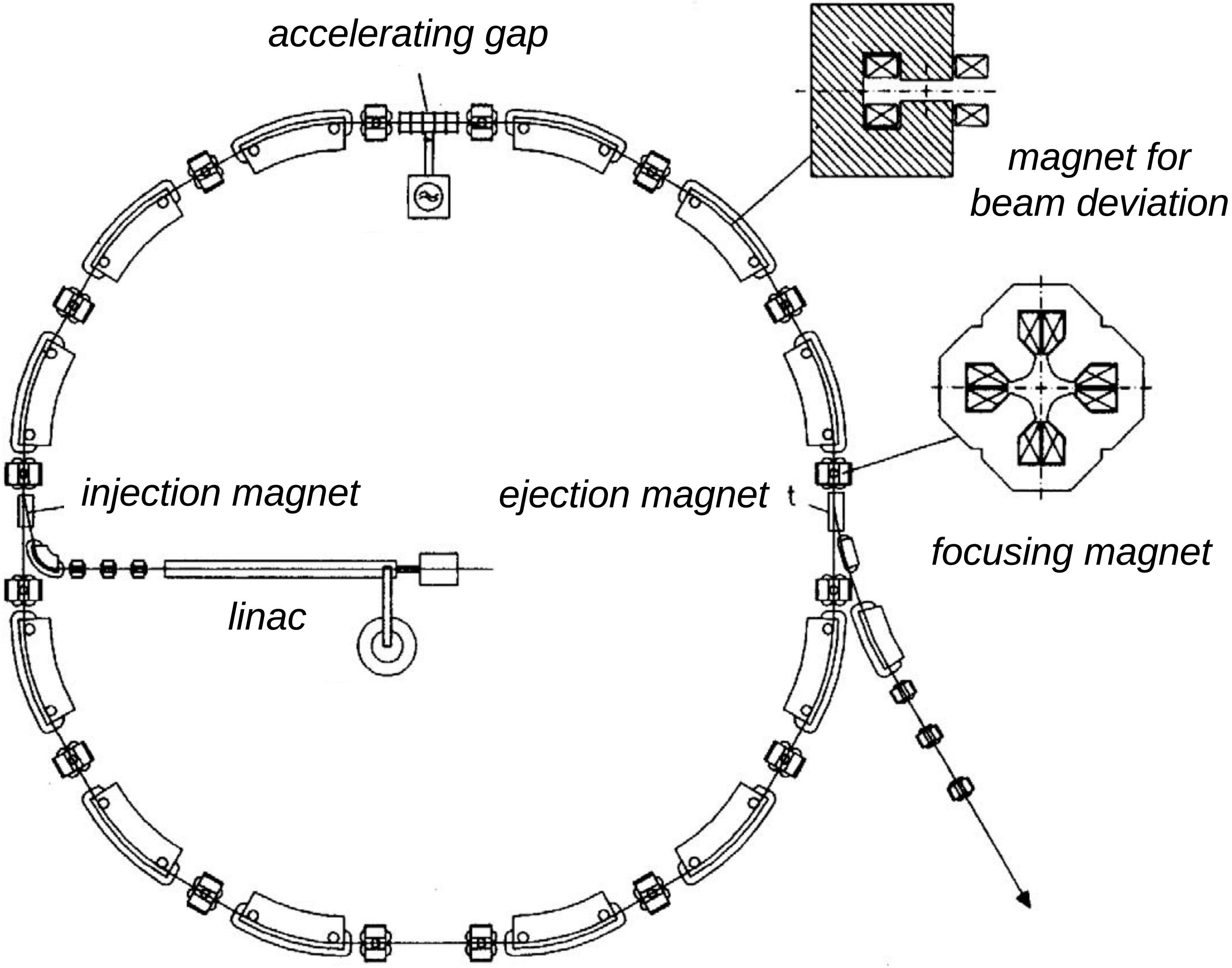
$$p = eBr \;\; \text{bzw.} \;\; p(GeV/c) = 0.3 \cdot B(T) \cdot r(m)$$

The orbit radius increases with the Energy and this can be compensated only by higher magnetic fields. Maximal B =5-10 T!!!! Moreover big jokes are very expensive.

The new idea is to keep the orbit constant and oblige the particle to run along the circle via dipole magnets. Along the path there are different accelaration gaps such that E/B stays constant. This means that the magnetic field has to be risen synchronic to the E field.

Synchrotron

(Wille, Teilchenbeschleuniger)



accelerating gap

magnet for
beam deviation

injection magnet

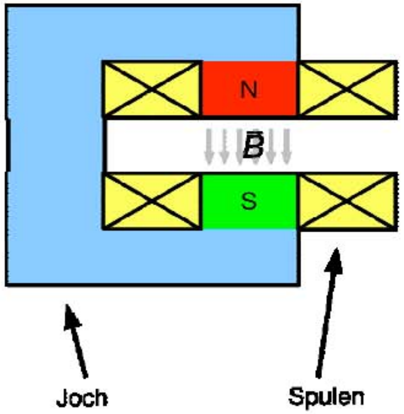
ejection magnet

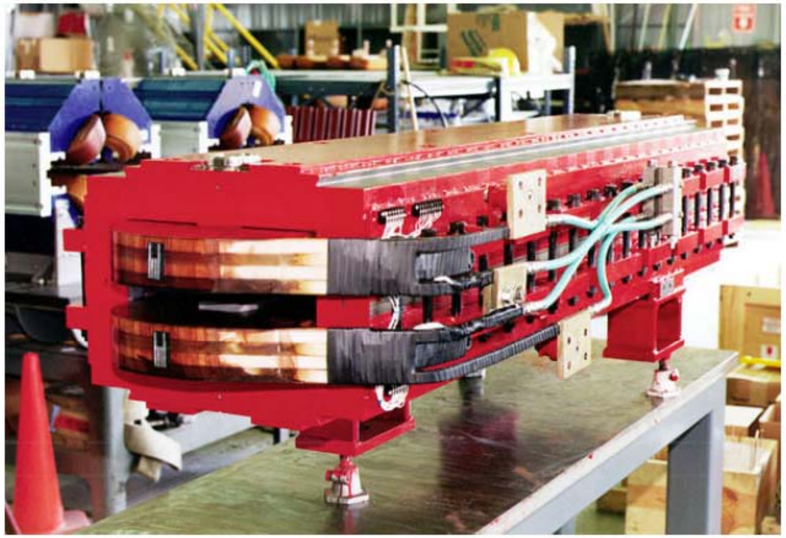
focusing magnet

linac

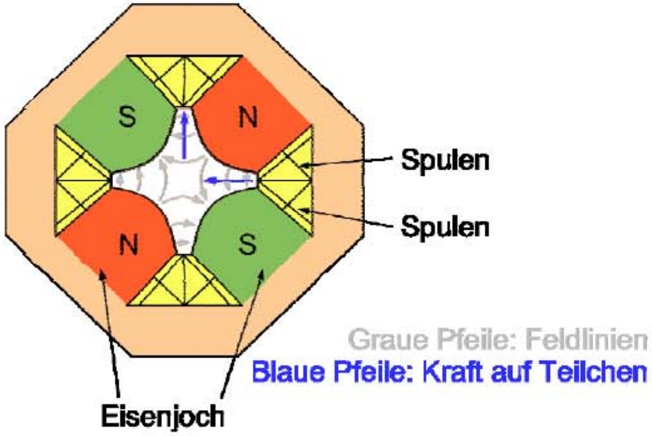
Dipole and Quadropole

Dipolmagnet

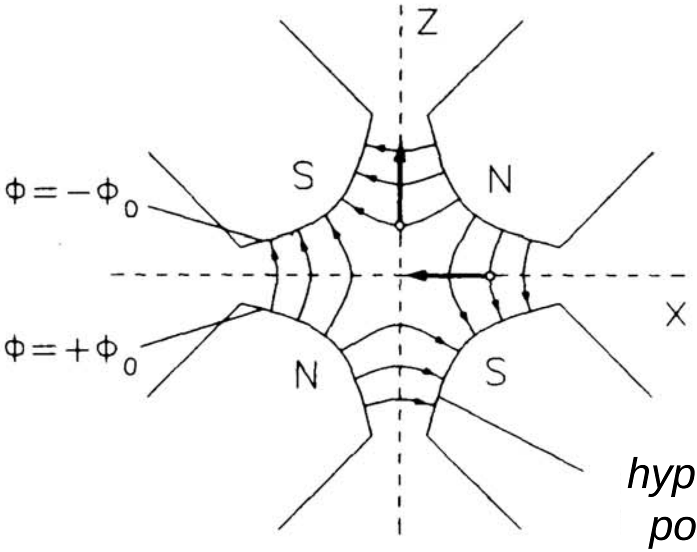


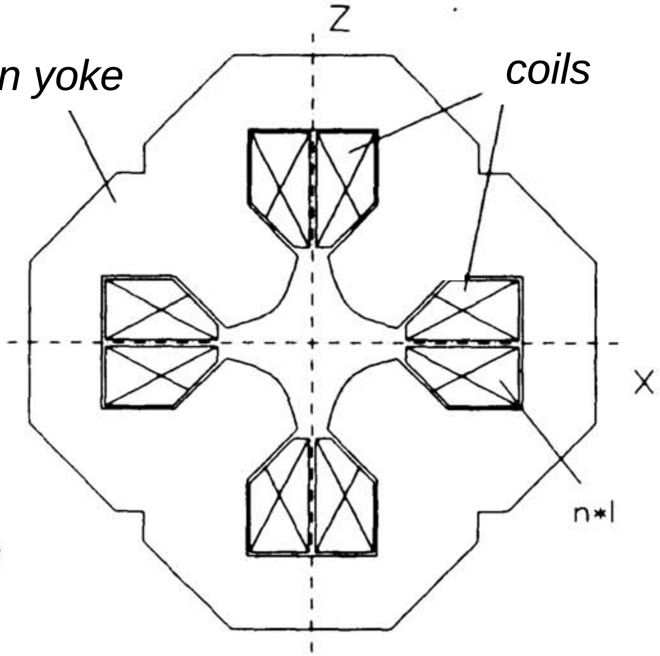


Quadrupolmagnet



Focusing





Since the quadrupole is focusing the beam in one direction and defocusing in the other, there are placed couple-wise after one another and turned of 90 deg.

Synchrotron Radiation

Since the particles are accellarated on a circular orbit, they radiate energy.
For each circle we have the following energy loss:

$$\Delta E_{synchr} = \frac{e^2}{3\varepsilon_0 (m_0 c^2)} \frac{E^4}{R}$$

Such energy loss is 10^{13} times larger for electrons than for protons.

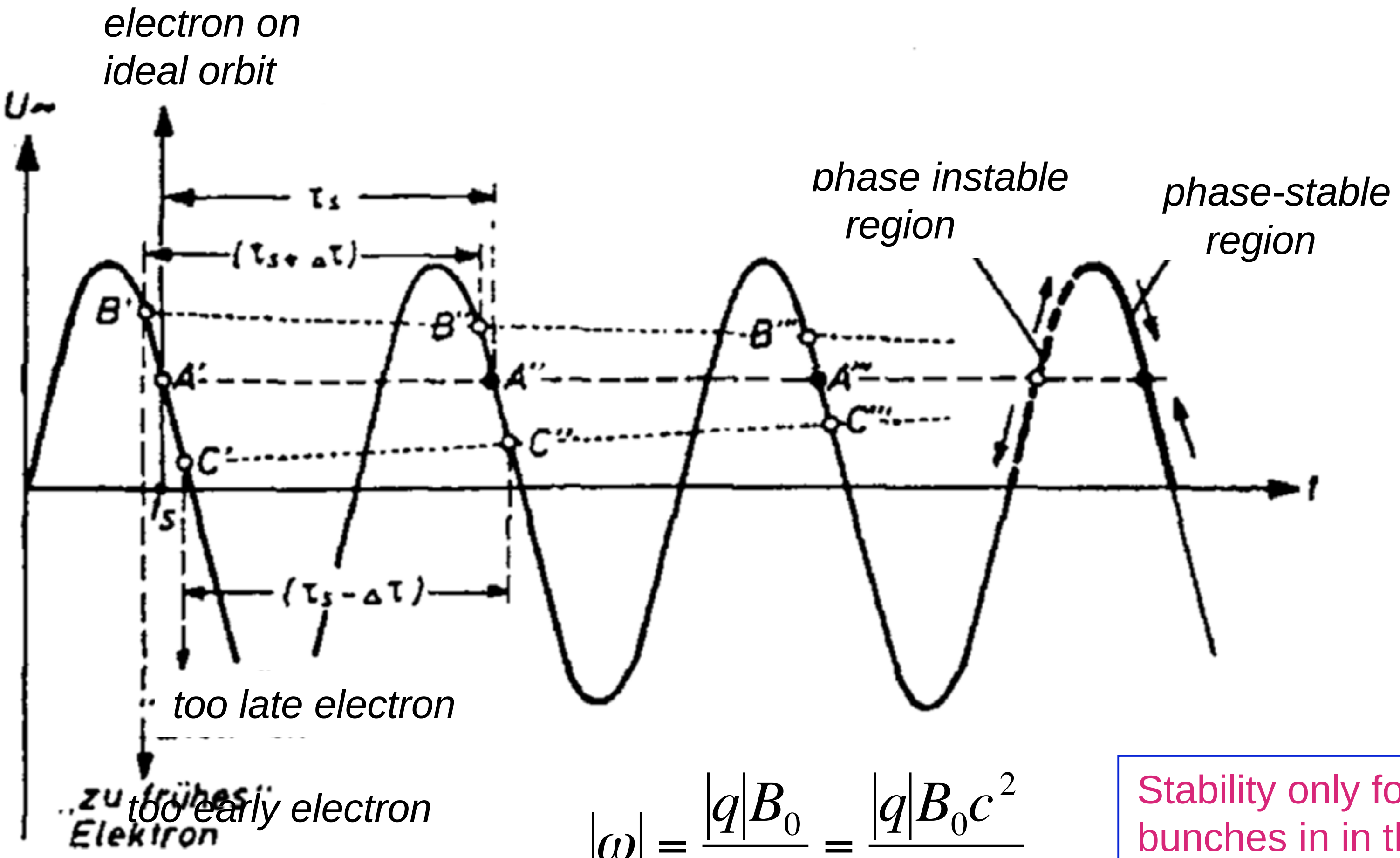
Despite of the fact that large radii can reduce such loss this implies a maximal reachable energy for electron of 100 GeV

$$\Delta E_{synch,e}(keV) = 88{,}5 \cdot \frac{E^4(GeV^4)}{R(m)}$$

$$\Delta E_{synch,p}(eV) = 7{,}79 \cdot 10^{-9} \frac{E^4(GeV^4)}{R(m)}$$

The limit in the accelleration of the protons is given by the steering magnets. Furthermore particles have to be pre-accellerated before entering the synchrotron, since the magnets cannot deflect particles with energy close to 0.

Phase Diagram of the Synchrotron



electron on
ideal orbit

phase instable
region

phase-stable
region

too late electron

too early electron

$$|\omega| = \frac{|q|B_0}{\gamma m} = \frac{|q|B_0 c^2}{E}$$

Stability only for bunches in in the orbit!

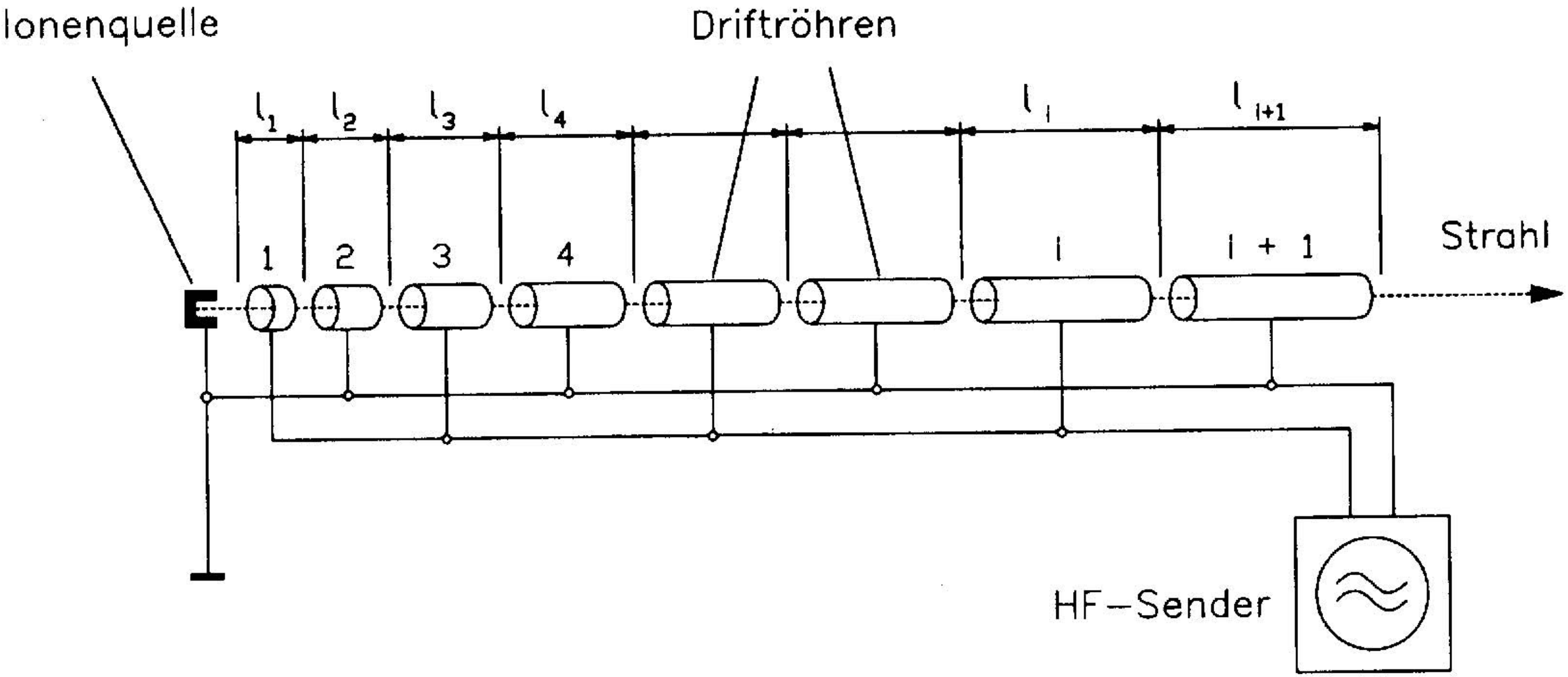
Lear (CERN)

Proton-Linac (Wille, Teilchenbeschleuniger)

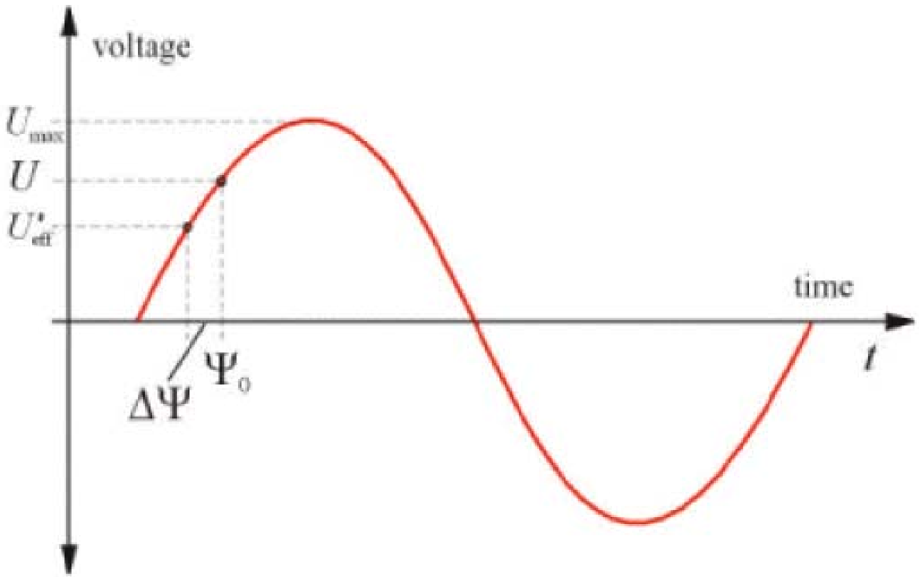
Good also for electron accelleration!

$E_{\text{MAX proton}}$=100MeV, used as injector for ring accellarators

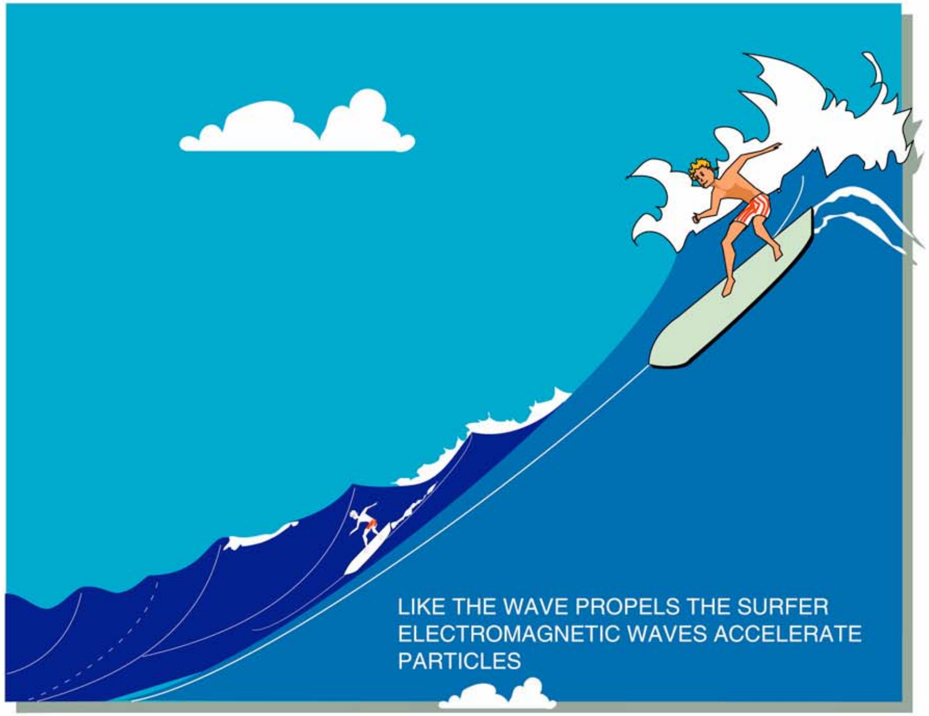
TESLA: 30 km electron LINAC for 500 GeV electrons



Phase Focusing

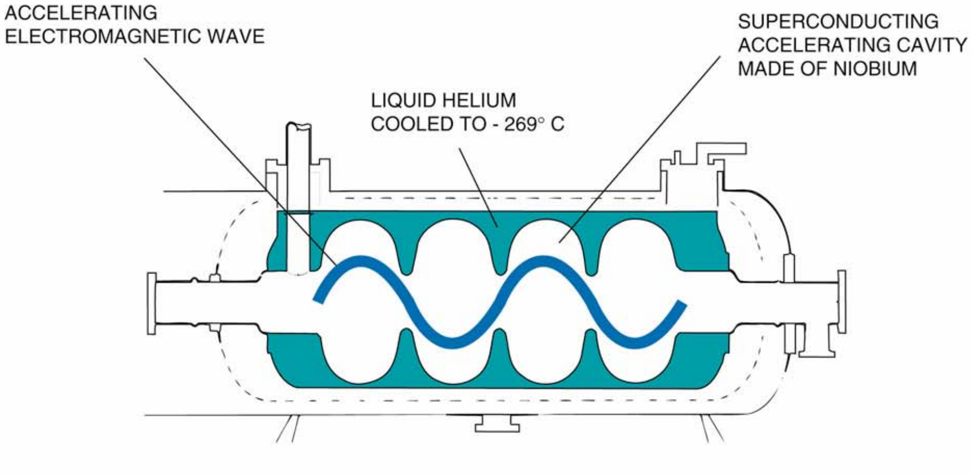


A particle that is faster and arrives earlier sees a smaller V and hence will be slowed down in the next cycle. This is again only possible for a BUNCHED beam.



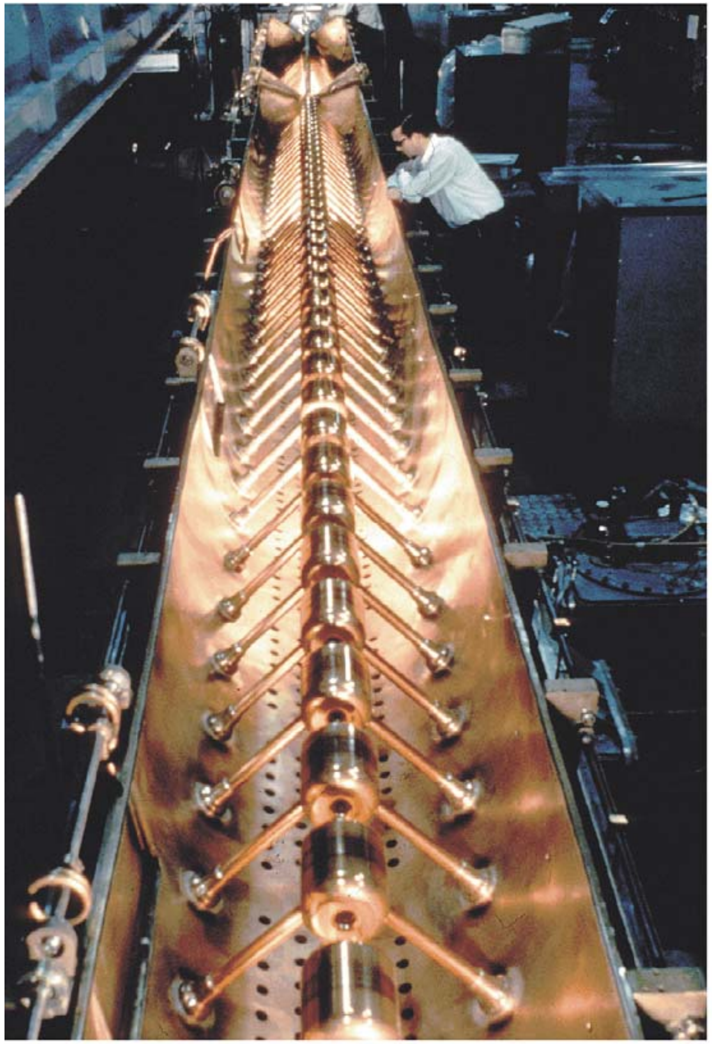
LIKE THE WAVE PROPELS THE SURFER ELECTROMAGNETIC WAVES ACCELERATE PARTICLES

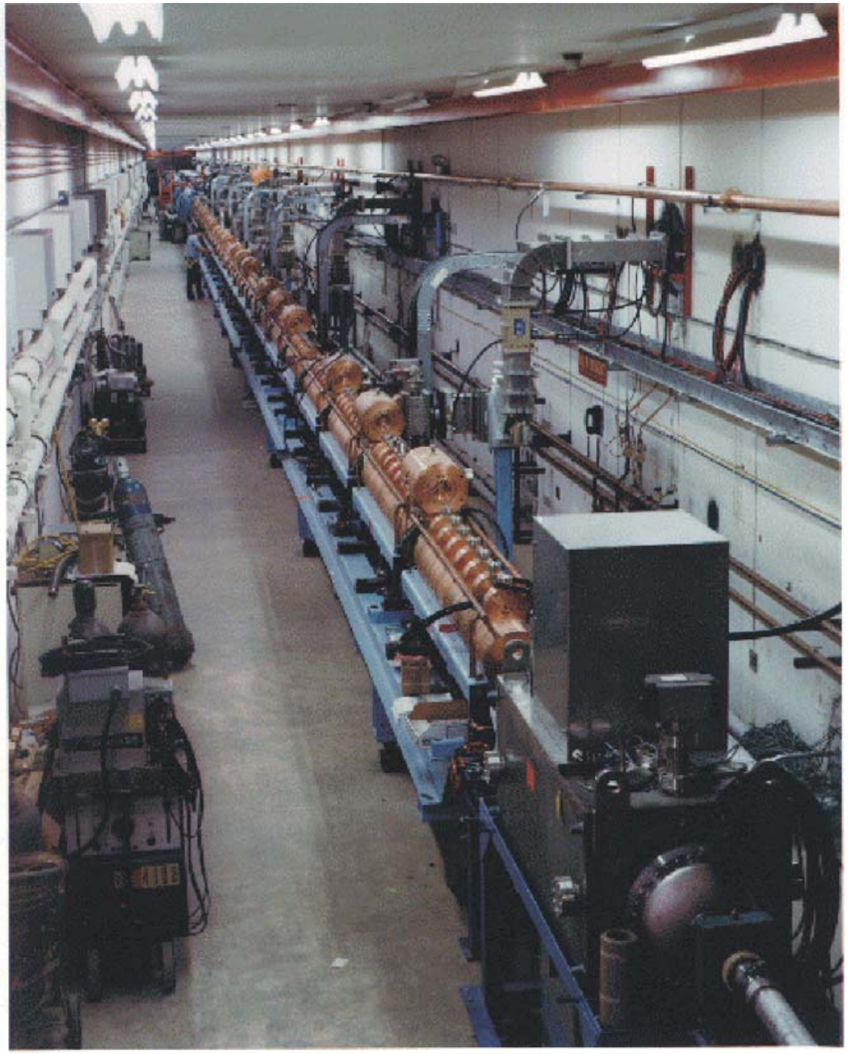
THE USE OF SUPRACONDUCTIVITY TO INCREASE PERFORMANCES AND CONSIDERABLY REDUCE ELECTRICITY CONSUMPTION



CERN AC _ Z31 VA_ V12/8/1997

Linacs at CERN



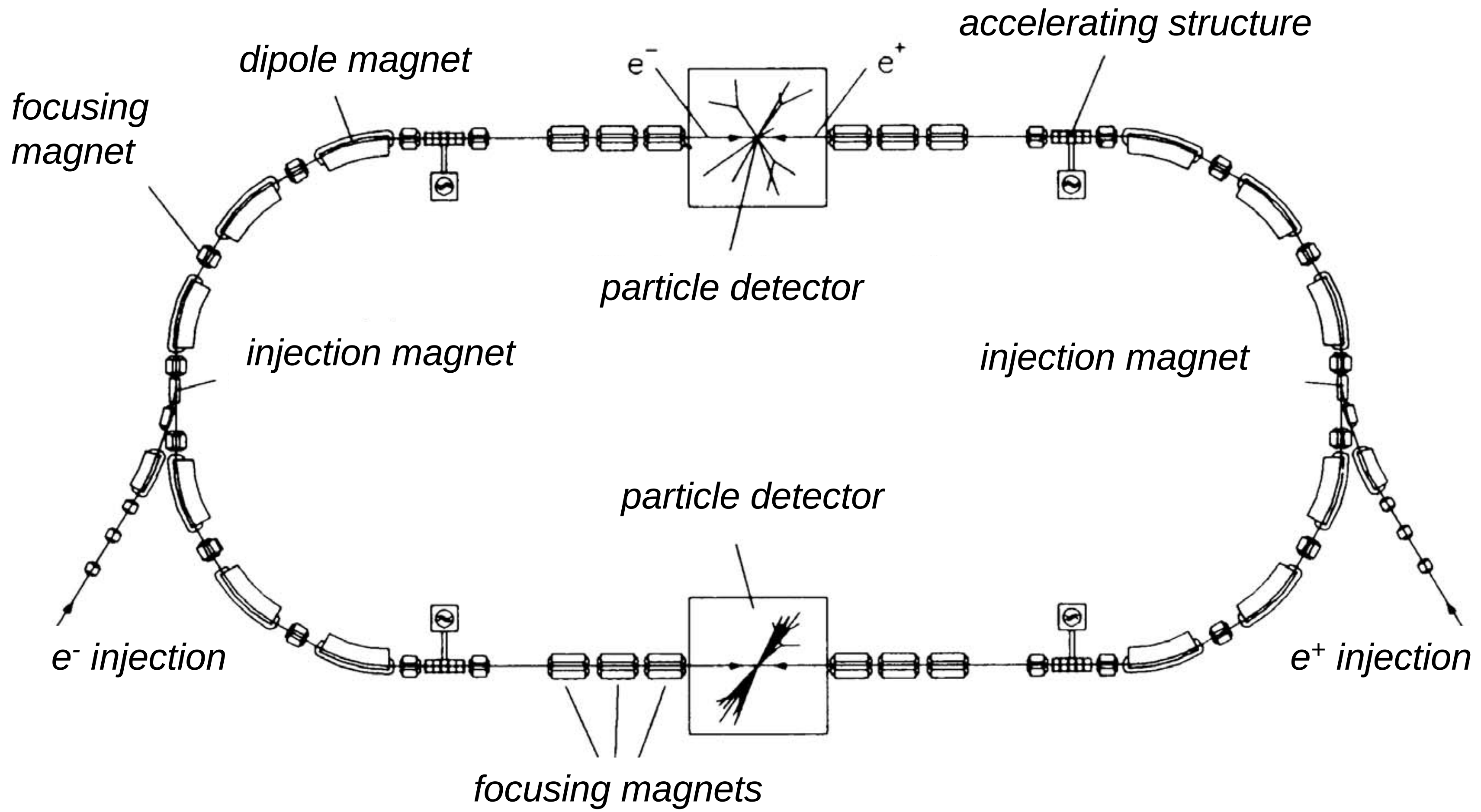


Largest LINAC at SLAC (Stanford Linear Accelerator Center)

L=3km, $\mathbf{E_{MAX\ electron}=50\ GeV}$

Collider

(Wille, Teilchenbeschleuniger)



dipole magnet

focusing magnet

accelerating structure

particle detector

injection magnet

injection magnet

particle detector

e^- injection

e^+ injection

focusing magnets

1. Energy:

in the cm system in terms of momentum 4-vectors $s = (p_1+p_2)^2$

fixed target: $s = (m_1c^2)^2 + 2\gamma_1 m_1c^2 m_2c^2 + (m_2c^2)^2$

special case of equal masses $\sqrt{s} = mc^2 \sqrt{(2+2\gamma)}$

high energy limit $\sqrt{s} = mc^2 \sqrt{(2\gamma)}$

colliding beams: $s = (m_1c^2)^2 + (m_2c^2)^2 + 2\gamma_1\gamma_2 m_1c^2 m_2c^2(1 + \beta_1\beta_2)$

high energy limit $s = 4E_1E_2$

special case of equal mass and energy $\boxed{\sqrt{s} = 2\,E = mc^2\,2\gamma}$

note: linear in γ

Luminosity

2. Luminosity:

fixed target: $\mathscr{L} = N_b[1/s]\ N_t\ [1/cm^2]$ beam rate times target thickness

$N_t = \rho\ t\ N_A/M$ e.g. for 1m liquid hydrogen $N_t = 2\ 10^{24}/cm^2$

typical for protons $N_b = 10^{13}/s \rightarrow \mathscr{L} = 2\ 10^{37}/cm^2s$

colliding beams: $\mathscr{L} = f\ n\ N_1N_2/A$

f frequency

n number of bunches in either beam around ring

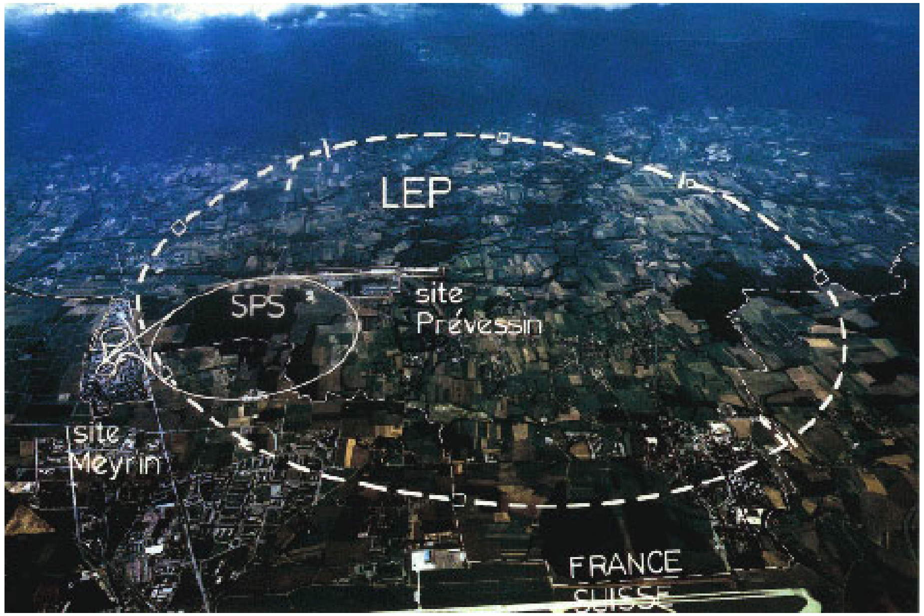
$N_{1,2}$ particles per bunch

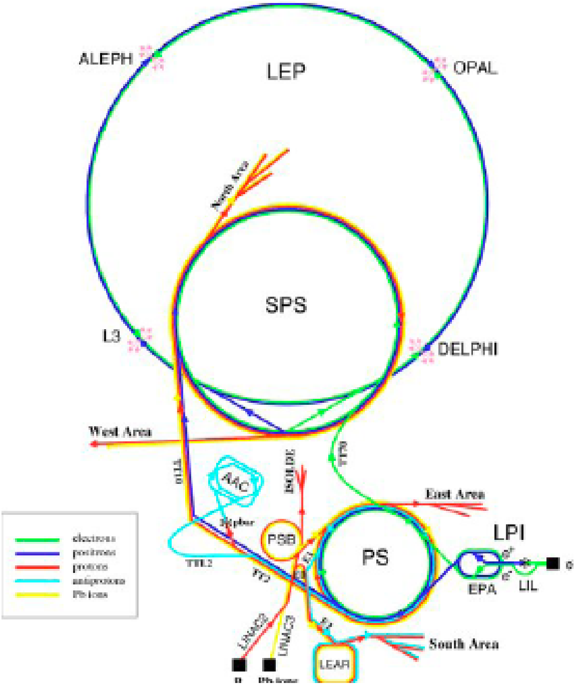
A cross sectional area of beam

typical	e^+e^- collider	$\mathscr{L} = 10^{31}/cm^2s$
	ppbar collider	$\mathscr{L} = 10^{30}/cm^2s$
	pp collider	$\mathscr{L} = 10^{33}/cm^2s$

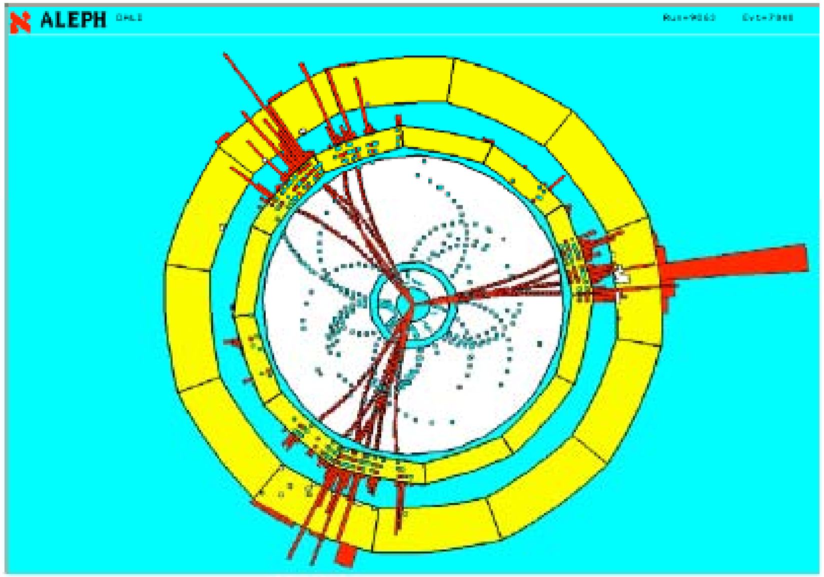
Large Electron-Positron Collider (LEP) am CERN

Betrieben von 1989-2000
Maximalenergie 100 GeV → $\sqrt{s} = 200$ GeV
Umfang 26.7 km, zwischen 40 und 150 m unter der Erde, 1,4% Neigung
3368 Magnete
272 Beschleunigerkavitäten
4 Kollisionspunkte mit Experimenten



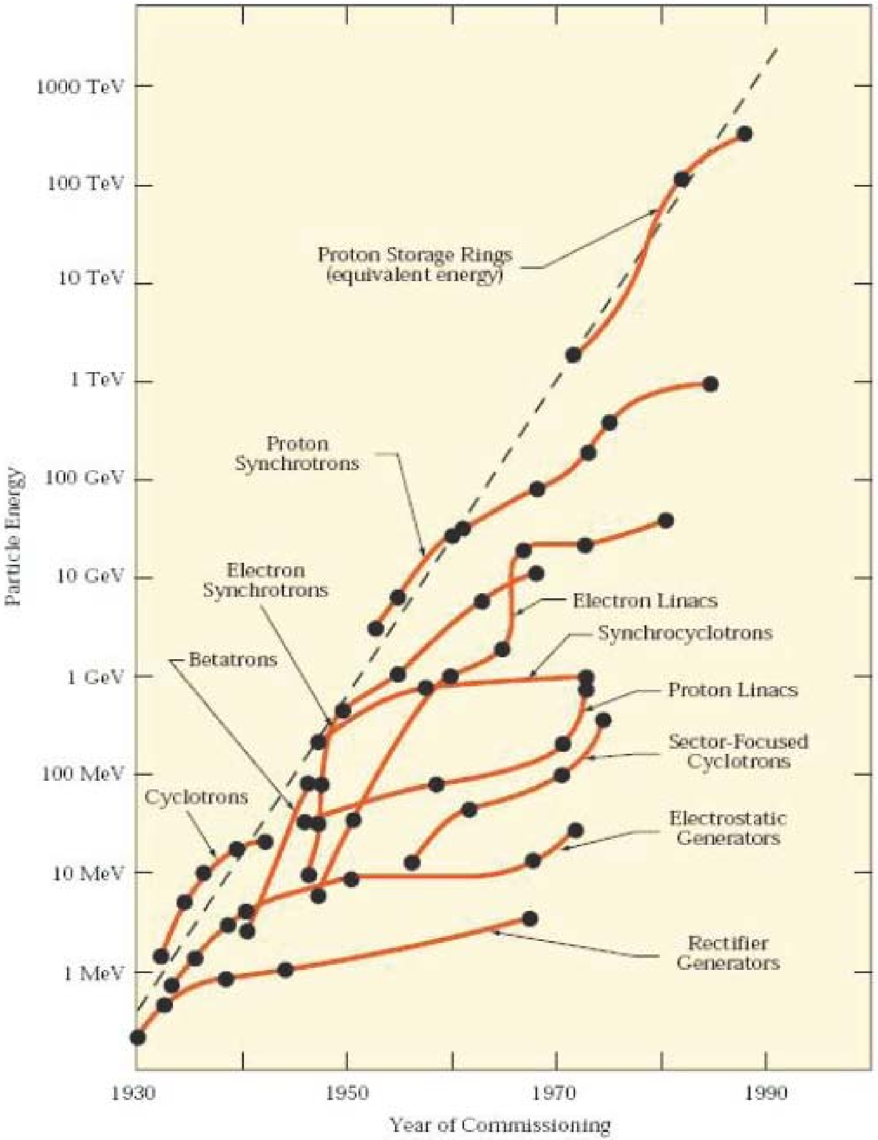


Aleph Detector at CERN LEP

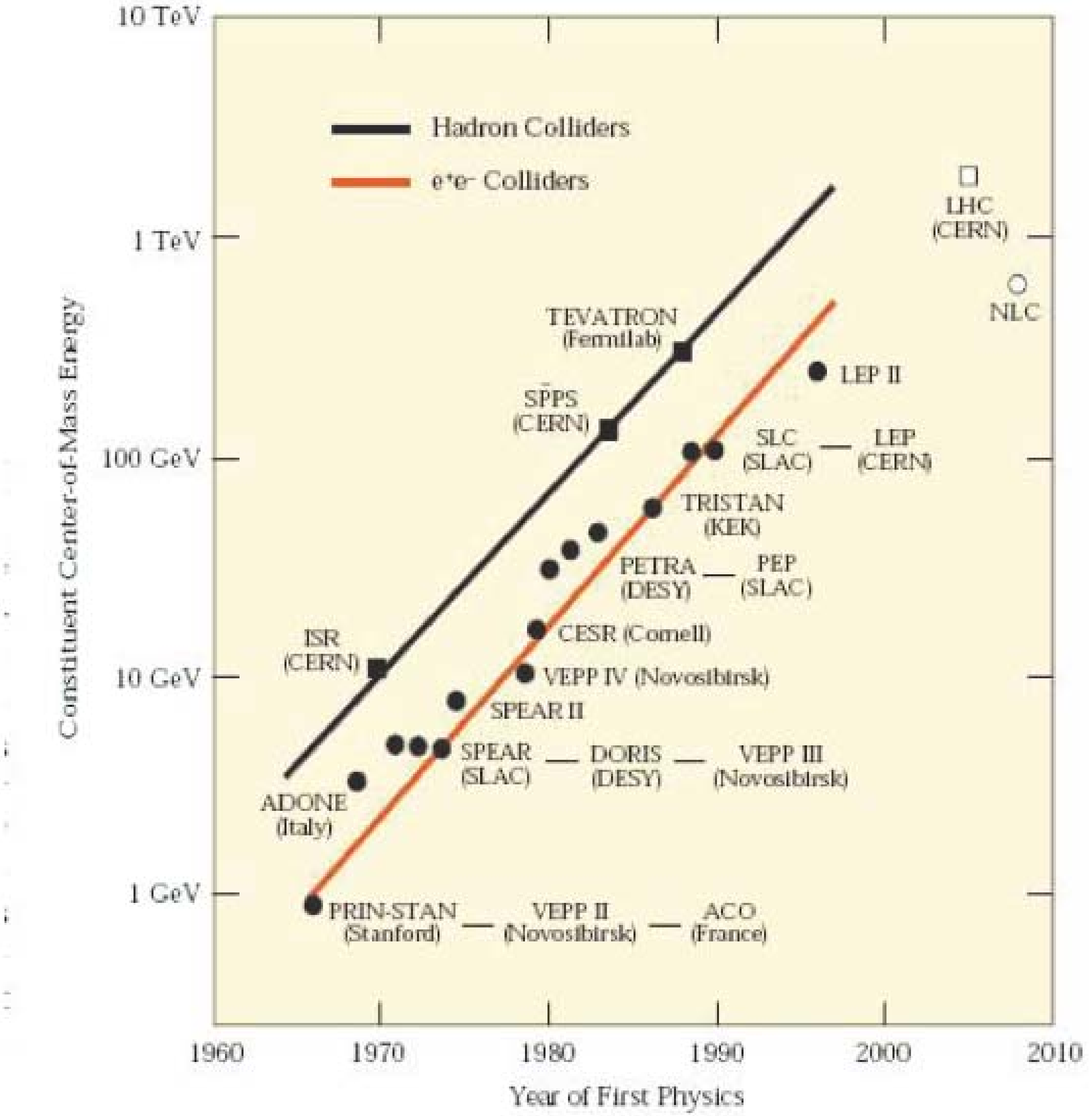


$$e^{+} + e^{-} \rightarrow Z^{0} \rightarrow q + \overline{q} + g \rightarrow \mathit{Hadronen}$$

Accellarator Evolution: Fixed target Experiment

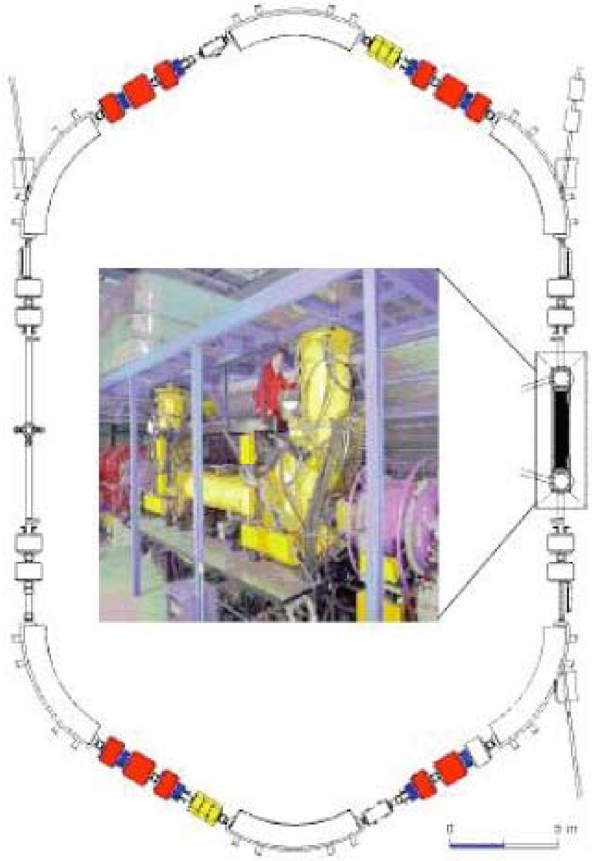


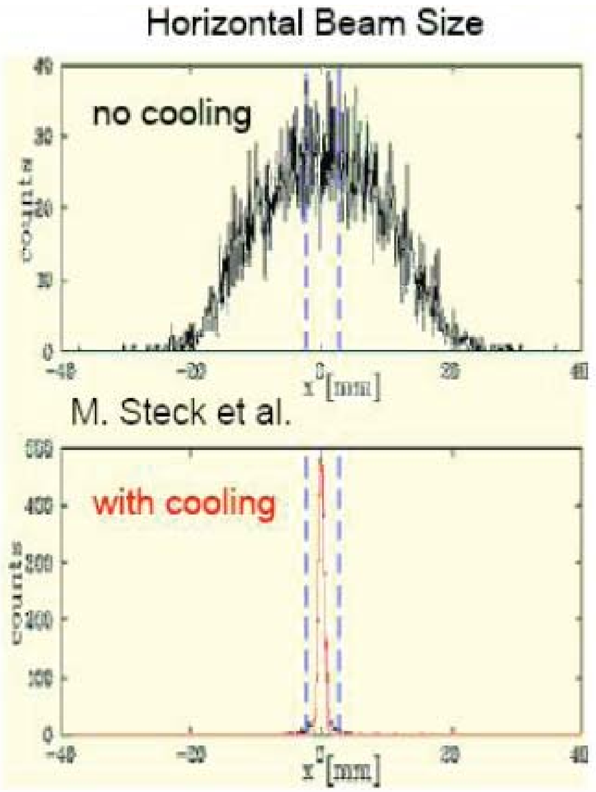
Accelarator Evolution: Colliders



Accellarator	*Energy, GeV*
Proton Synchrotrons	
CERNS PS	*28*
BNL AGS	*32*
KEK	*12*
SPS	*450*
Tevatron II	*1000*
Electron Accelarators	
SLAC linac	*25-50*
Desy Synchrotron	*7*
Colliding-beam machines	
PETRA	e^+e^- 22+22
LEP II	e^+e^- 100+100
HERA	*ep 30e+820p*
LHC	*pp 7000+7000*

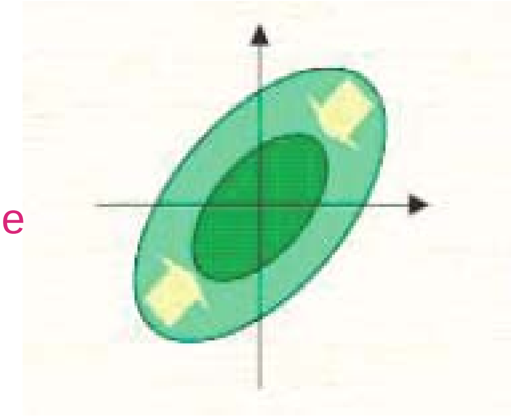
Electron Beam Cooling at ESR GSI





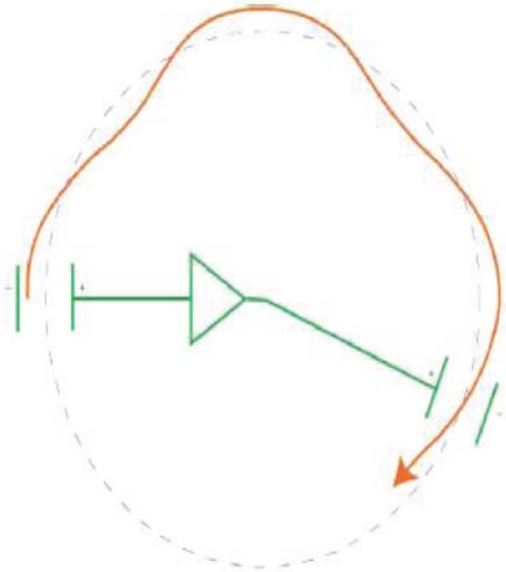
Cooling in the ESR counteracts the beam heating effect of the experimental insertions

Momentum spread due to the thermal motion.
Cooling should reduce the spread and hence increase the phase-space density



Principle of the stochastic Cooling

- *Measure beam center by pick-ups*
- *Correction signal to opposite kicker*



S. van der Meer included in Nobel prize for W,Z