F. Méot

CEA & IN2P3, LPSC

An introduction to particle accelerators

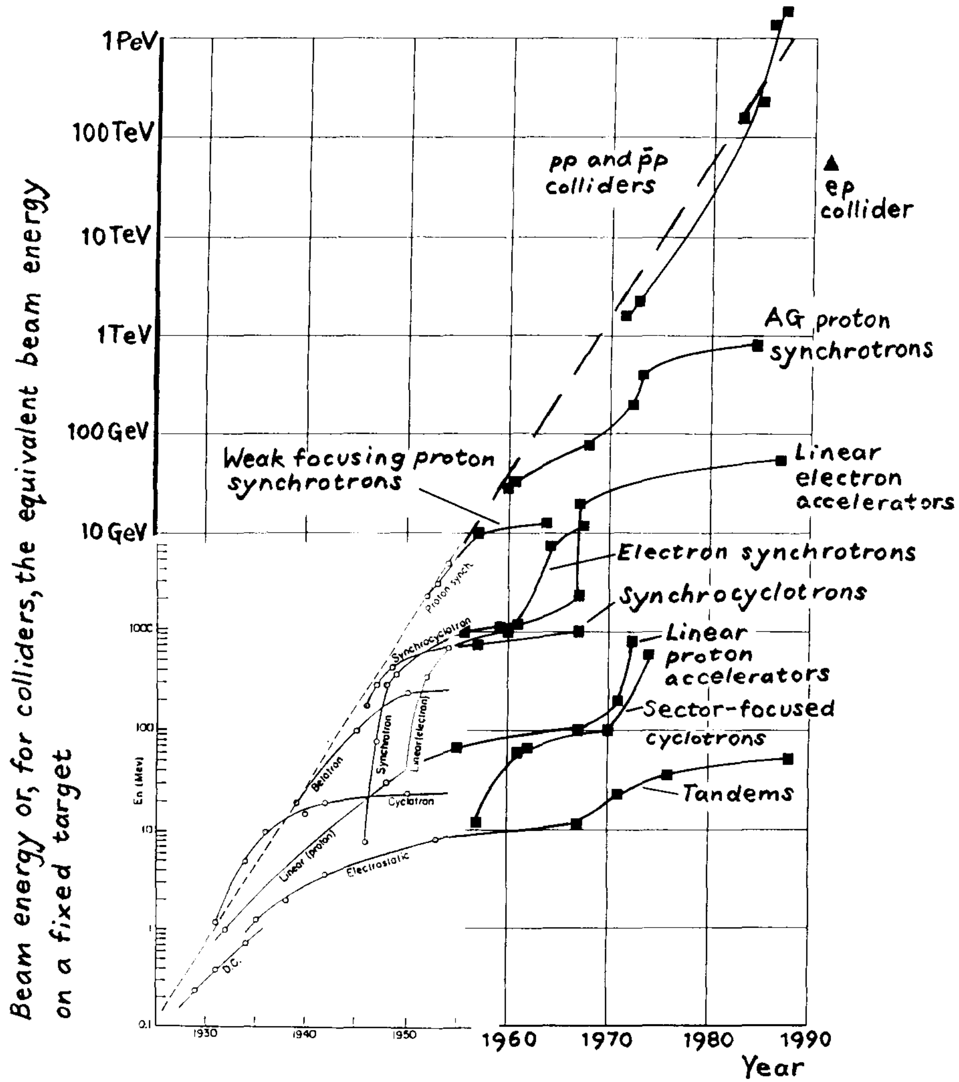
Contents

1 Generalities

- Particle accelerators were born in the quest of “atom smashers”, in a context of needs for higher and higher energies, beyond natural radioactivity bodies, in the several MeV range :

  for producing high energy $e-$ and ion beams, probing the atomic nucleus, creating new elements and isotopes

  For reference : high energy alpha from radioactive particles were $\sim$10 MeV.



- In the era of nuclear R&D, civil and military, they allow(ed) extensive production of data on radio-isotopes, production cross-sections...
- Very high energies have opened the field of accelerator based particle physics
- Energies have increased exponentially over the years, more or less saturating depending on the technology
- Later, with discoveries as synchrotron radiation, hadron-therapy, and given their potential for number of applications, accelerators found themselves predilection tools in many domains of science : production of X-rays, medical, industry...

The world of accelerators

	Kinetic energy			
	Electrons	protons and ions	What for	Records
Cockcroft-Walton		1 MeV	Material science, injector	
Van de Graaff		20-35 MeV	- id -	
Betatron	10 - 300 MeV		X-Ray generator	Industry
Microtron	20 - 1500 MeV		Science, industry	MAMI, 1.5 GeV
Cyclotron		10 - 560 MeV	Material-, bio-sci., medical	PSI, 590 MeV/1.2 MW
Synchro-cyclotron		100 - 750 MeV		
Synchrotron	1 - 10 GeV	1 - 500 GeV	acceleration, booster	SPS, 450 GeV
Storage ring	1 - 8 GeV		SR	Spring-8 LS, 8 GeV
Colliders rings	1 - 200 GeV	60 GeV - 14 TeV	HEP, factories	LEP II, 200 GeV / LHC, 14 TeV
e-Linacs	few MeVs		Industry, medic., science	
Linacs	20 MeV - 50 GeV	50 - 800 MeV	HEP, X-FEL	SLAC, 50 GeV / LAMPF, 800 MeV
Linear collider	50 GeV - 1 TeV		HEP - projects	SLC, 100 GeV - CLIC, 1 TeV
HPPA, synchrotron		1 GeV	Material science, μ, n, ν, ADS	ISIS, 800 MeV/160 kW
HPPA, linac		1 GeV	idem	SNS, 1 GeV/1.4 MW

Generalities

- We will follow a common classification that distinguishes four major concepts in the develoment of accelerators :
  - Electrostatic accelerators
  - Resonant acceleration
  - Phase stability
  - Strong focusing

  However, from the beginning, and this is still true nowadays, researches were held in several directions, in parallel :
  - 1924, Gustav Ising, tentative resonant linac acceleration, failed on operating
  - 1928, Wideröe, first linac ever, resonant acceleration, and tentative betatron
  - 1932, John Douglas Cockcroft and Ernest Thomas Sinton Walton, Cavendish Lab., pushed by Rutherford, voltage multiplier, first transmutation with 700 keV proton beam
  - 1930, Ernest O. Lawrence invents the cyclotron
  - 1929 - 1931, "Van de Graaff" electrostatic generator model, two spherical bulbes Φ60 cm, reached 1.5 MV
  - 1932, E.O. Lawrence & M.S. Livingston, Univ. of California, operation of the first cyclotron, 1.25 MeV protons. Nuclear reactions just a few weeks after John Cockcroft and Ernest Walton
  - Etc... this is the goal of this lecture to give an overview of all this and the rest...

2 Prehistory

α particles were the first projectiles

• 1900s Rutherford figures out that α-particles are He nuclei.

• 1910 Rutherford and Madsen first smash atoms with α-particles to gain insight in the atom structure from scattering patterns. They detect the presence of a nucleus.

• 1910s Rutherford and Madsen kick out protons from various elements by that very method

• 1930s Bothe and Becker, Joliot-Curie family, Chadwick knock out neutrons by bombarding Be nuclei : $\alpha + ^9Be \longrightarrow ^{13}C + n$.

Chadwick convincingly shows that the emerging particles were neutrons.

Cosmic rays

• 1900s, Presence of radiation observed, using electroscopes and electrometers, even away from any radioactive source.

• 1932 Anderson discovers positron, predicted by Dirac

• 1937 Anderson and Neddermeyer discover a particle with $220\times$ the electron mass, from cosmic ray snaps: the muon

• 1947 Lattes, Occhialini, Powell discover charged pions (today's $\bar{u}d$ and $\bar{d}u$ quark pairs)

• 1940s Discoveries of strange particles: $K^\pm, K_0, \Lambda, \Sigma^+$ (hadrons with one strange quark)

• The difficulty of these paths was that one had no control over the projectiles, their energies, their rate was rather scarce

• Hence the interest of accelerators for creating new particles. Milliampers of MeV particles from accelerators is equivalent to thousand-Curie radioactivity.

3 Electrostatic accelerators

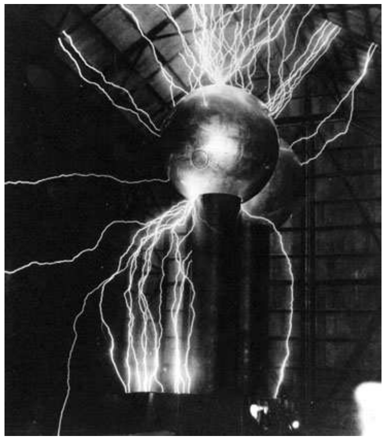
A BRIEF INTRODUCTION

- Creating strong electrostatic potential : simplest and most obvious method. This is a way to communicate energy to charged particles, by virtue of

$$\vec{F} = -q\,\vec{grad}V, \quad W = q\,V$$

- There was a broad context of development of high voltage generators :
  - Whimshurst wheel (1880s - 10s kV, few tens μAmp), Marx generator (1924 - a variant of a voltage-multiplier), Tesla coil (induction high voltage) ...
  - Two methods succeded : Crockcroft-Walton voltage multiplier, Van de Graaff electrostatic generator.

- Limitation on potential achievable for particle acceleration resides in
  - ohmic losses in apparatus structure - proportional to potential
  - current from ionized gas - limited by saturation
  - corona discharge - the major cause



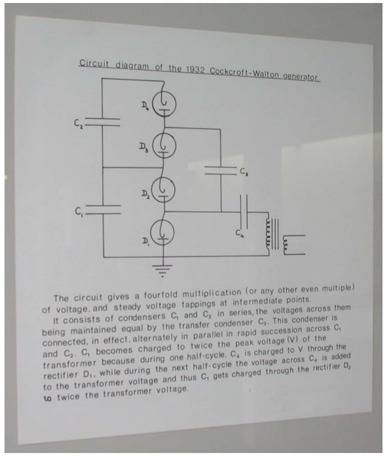
Cockcroft-Walton (1/3)

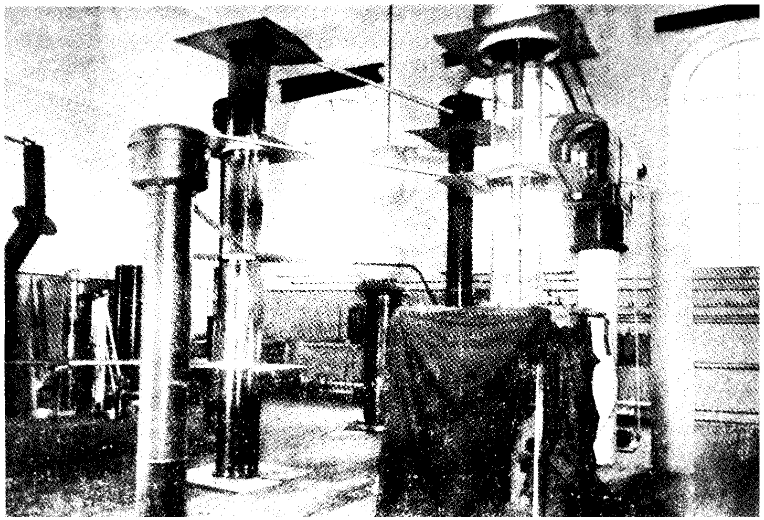
John Douglas Cockcroft
Ernest Walton


- A particular type of “voltage multiplier” (also known as “Greinacher multiplier”, earlier proposed by Heinrich Greinacher, Swiss, 1919), coupled to accelerating gaps, at Cavendish Lab., 1932 :

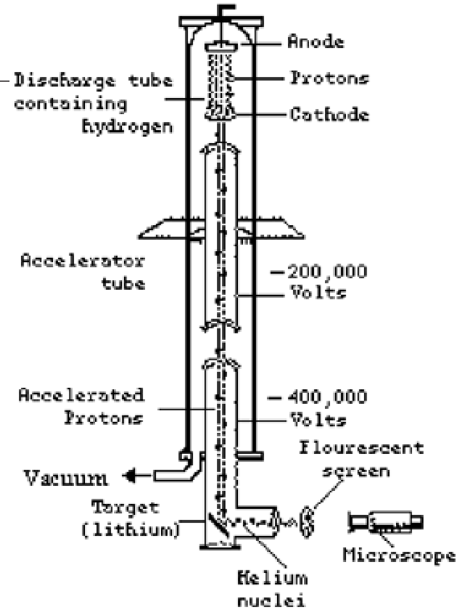
- interest of *accelerator method* proven by allowing first artificial nuclear transmutation, ${}^{7}_{3}Li \; + p \longrightarrow 2 \times \alpha + 17\ \mathrm{MeV}$

- Only 20 years later, 1951, did they get the Nobel prize “for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles”.





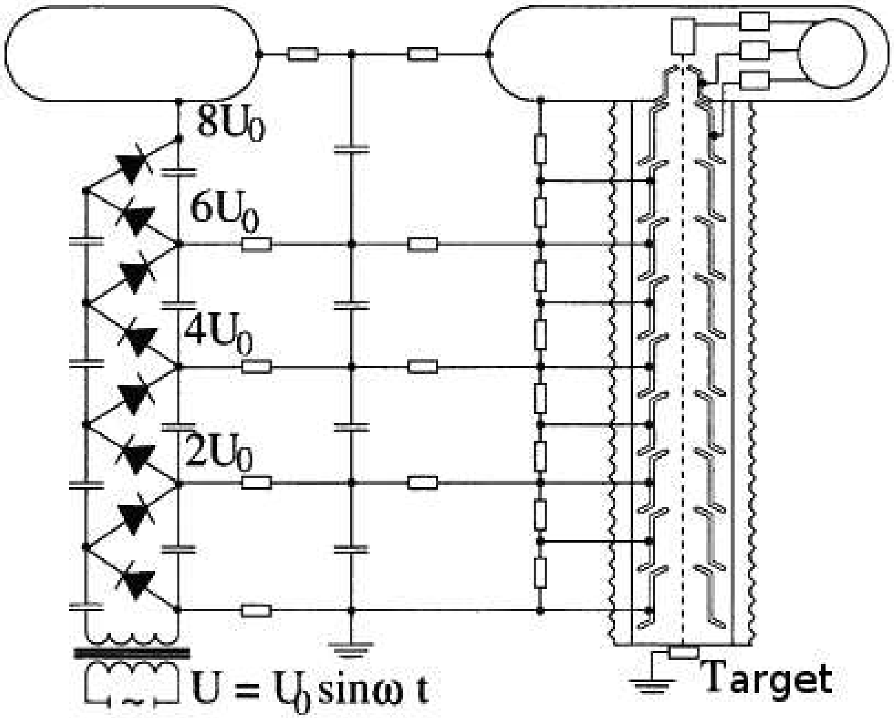
Voltage-multiplier circuitry and installation.
$\gtrsim$700 kV from a 200 kV transformer were obtained,
$\sim 10\mu A$ proton beam.
Penetration probability $1.8\,10^{-7}$ at 700 kV $\stackrel{10\mu A}{\longrightarrow} 10^7$ events/s.



A scheme of C-W’s 2-gap accelerator column.
Potential for Li decay experiment was ~700 kV

Cockcroft-Walton (2/3), principle

The figure below shows principle assembly of (modern-style) Cockcroft-Walton voltage multiplier driven by AC voltage supply (left) and typical multi-electrode accelerator column (right).



Nowadays technologies allow up to U_{total} ~5 MVolts, several tens mA DC (>100 kW beam).

Principles :

The maximum voltage is $2 \times n \times U_0$, plus a correction for current induced loss :

$\boxed{U_{total} = 2 \times n \times U_0} - \frac{2\pi I}{\omega C} \times f(n)$

C = value of a capacitor

n = number of stages

I = ohmic loss + beam

f = $\sim n^3$ polynomial dependence $\Rightarrow$ limitation on n : voltage drop with I grows fast with the number of stages

It shows that large C and large ω reduce the effect of I on U_{total}.

Accelerator application : stability $\frac{\delta U_{tot}}{U_{tot}} \approx \frac{2\pi n^3}{RC\omega} \approx$few%

Focusing : "cylindrical lens" principles

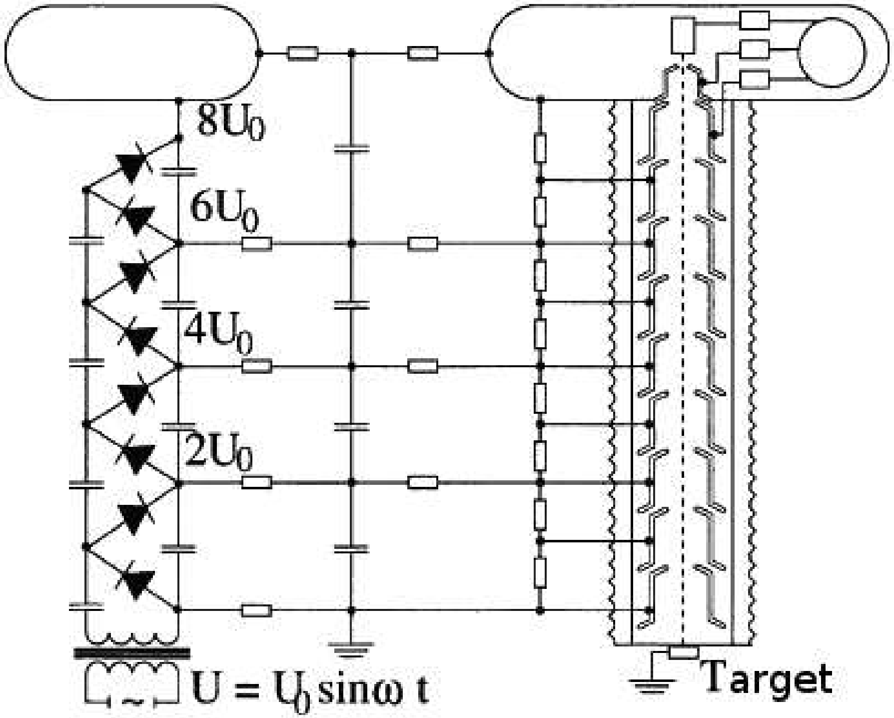
Exercise :

Take impedance $R \sim$GΩ, capacity $C \sim$nF.

What is the order of magnitude of generator frequency $\omega/2\pi$ for $\frac{\delta U_{tot}}{U_{tot}} \sim 1\%$?

Cockcroft-Walton (2/3), principle

The figure below shows principle assembly of (modern-style) Cockcroft-Walton voltage multiplier driven by AC voltage supply (left) and typical multi-electrode accelerator column (right).



Nowadays technologies allow up to U_{total} ~5 MVolts, several tens mA DC (>100 kW beam).

Principles :

The maximum voltage is $2 \times n \times U_0$, plus a correction for current induced loss :

$\boxed{U_{total} = 2 \times n \times U_0} - \frac{2\pi I}{\omega C} \times f(n)$

C = value of a capacitor

n = number of stages

I = ohmic loss + beam

f = $\sim n^3$ polynomial dependence $\Rightarrow$ limitation on n : voltage drop with I grows fast with the number of stages

It shows that large C and large ω reduce the effect of I on U_{total}.

Accelerator application : stability $\frac{\delta U_{tot}}{U_{tot}} \approx \frac{2\pi n^3}{RC\omega} \approx$few%

Focusing : “cylindrical lens” principles

Exercise :

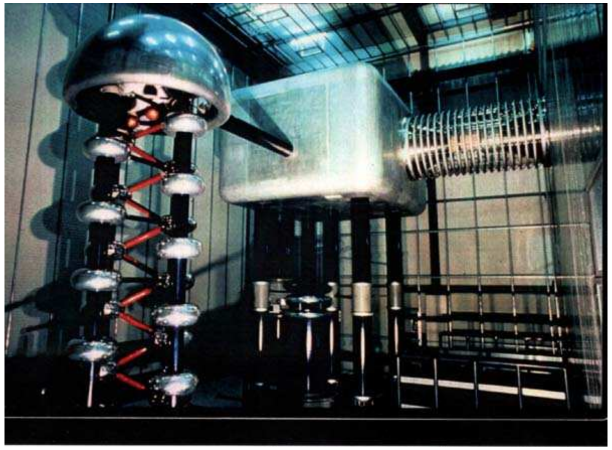
Take impedance $R \sim$GΩ, capacity $C \sim$nF.

What is the order of magnitude of generator frequency $\omega/2\pi$ for $\frac{\delta U_{tot}}{U_{tot}} \sim 1\%$.

Response : kHz range.

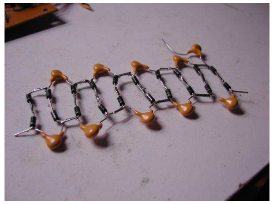
Cockcroft-Walton (3/3)

- Cockcroft-Walton voltage multiplier is one amongst various other types of voltage multipliers
- A technique convenient in accelerator installations, still in use today in number of laboratories, at the front end of the injection chain. Allows reasonably high intensities.



A modern version :
the 810 kV, 30 mA Cockcroft-Walton injector at the PSI Mega-Watt cyclotron, using a voltage multiplier.

Exercise : value of n , U_0 ?



Some more easy kVs...

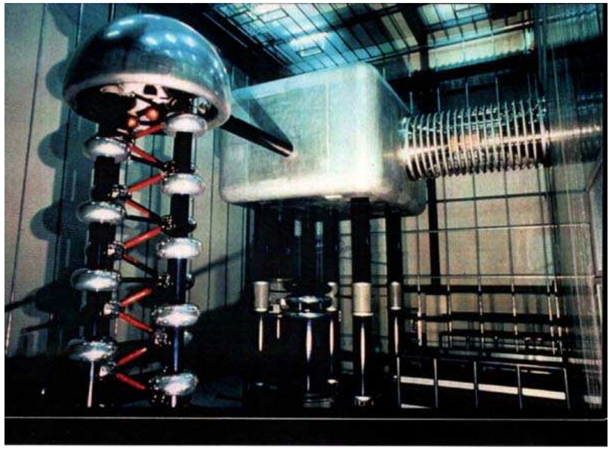
Tevatron injector at FermiLab (source, C-W and transfer lines are doubled for minimal down-time). H-, 20 keV DC beam, accelerated to 750 keV prior to bunching and injection into a DTL.

And a trend, replacement by RFQ :

"[...] to reduce the maintenance requirements of the 750-keV pre-accelerator system, the replacement of the present Cockcroft-Walton accelerators with a single RFQ accelerator is proposed." (December 2008)

Cockcroft-Walton (3/3)

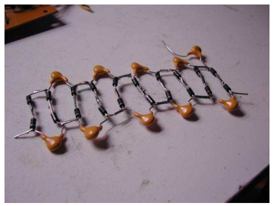
- Cockcroft-Walton voltage multiplier is one amongst various other types of voltage multipliers
- A technique convenient in accelerator installations, still in use today in number of laboratories, at the front end of the injection chain.



A modern version :
the 810 kV, 30 mA Cockcroft-Walton injector at the PSI Mega-Watt cyclotron, using a voltage multiplier.

Exercise : value of n , U_0 ?

Resp. : n=5, $U_0 \sim 80$ kV



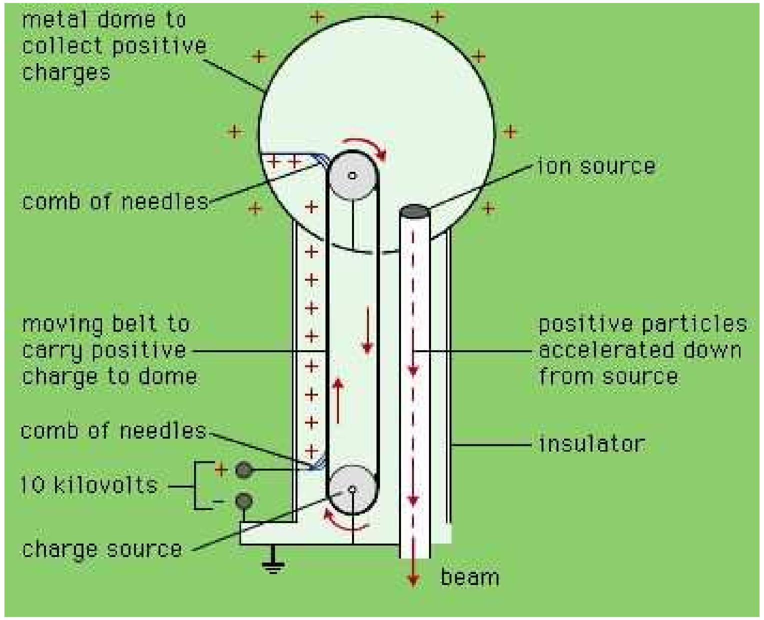
Some more easy kVs...

FermiLab injector (source, C-W and transfer lines are doubled for minimal down-time).
H-, 20 keV DC beam, accelerated to 750 keV prior to bunching and injection into a DTL.

And a trend, replacement by RFQ :

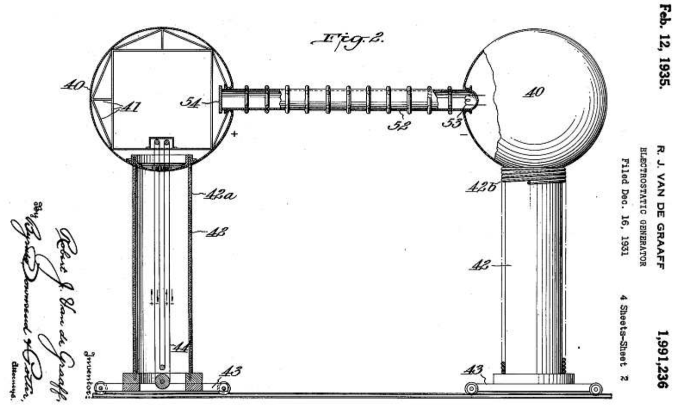
“[...] to reduce the maintenance requirements of the 750-keV pre-accelerator system, the replacement of the present Cockcroft-Walton accelerators with a single RFQ accelerator is proposed.” (December 2008)

Van de Graaff (1/2)

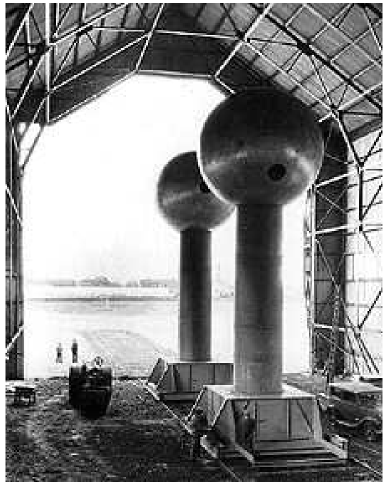


Van de Graaff electrostatic generator, principle : $+$ or $-$ charges, as brought by the insulating belt, are stored at the outer surface of the bulbe. Sharp points of combs are close to, but not touching, the belt, charges are transported from and to the belt by corona effect. Potential is used to accelerate particles.

In the company of its developper...



Patent figure, Dec. 1931.



A 2×3.5 MV specimen, 1933.

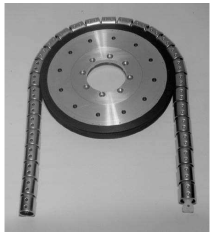
- The Van de Graaff generator is simple, easy to regulate, capable of producing high voltages and therefore high accelerations of electrons or ions (compared at that time to Cockcroft-Walton).
- It is preferred when low ripple (low energy spread) is important at megavolt potentials.
- Intensity limited to $\sim$mA.
- Effects limiting maximum achievable voltage are, size !, leackage, insulation, shape of electrodes...

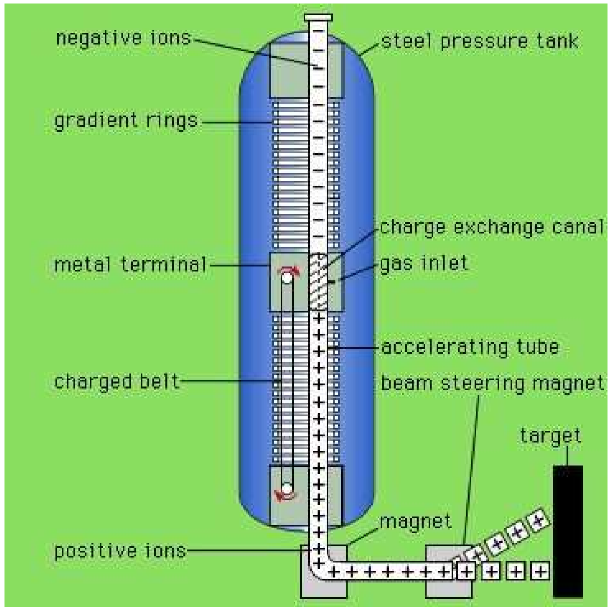
Van de Graaff (2/2), Tandem

- There are nowadays hundreds of Van de Graaff accelerators over the world.
- Often under the form of “tandem Van de Graaff” : doubles available energy,

and gas pressurised (isolating gas SF6, freon, several 10^5Pa) : limit corona effects, reduce size, source and target at ground potential.

In the “Pelletron” (1960’s), a pellet chain replaces the belt and induction devices replace the needle combs (yields better stability, reliability...)



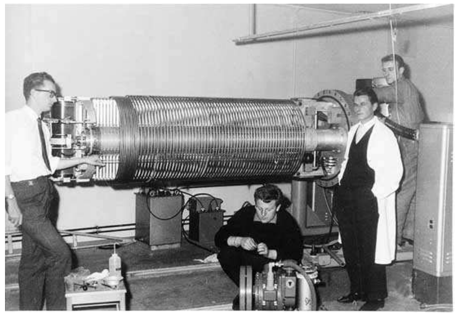


Two-stage - “tandem” - pressurized Van de Graaff.

One of the two (face-to-face) stages of the 15 MV Tandem-Van de Graaff at BNL. Can accelerate 40 different types of ions.

The tandem Van de Graaff at Western Michigan University, used for basic research, student training...

20 MV tandem VdG at Tandar Lab., Argentina (above), a smaller ancestor in earlier times (below).



4 Resonant acceleration

A BRIEF INTRODUCTION

- The principle of the resonant acceleration consists in having the particle motion satisfy some synchronism condition with a time-varying electric field.

  Namely, acceleration comes from cyclic accumulation of small “longitudinal kicks”, rather than a single, big one

- First attempts are due to Gustav Ising in Stockholm, 1924.

- In 1928 Rolf Wideröe realizes the first experimental demonstration based on Ising’s concept of resonant acceleration.

- This new concept was a real big step in methods of acceleration : it avoided the use of high voltage.

- It lead in 1930 to the first practical resonance accelerator, the cyclotron...

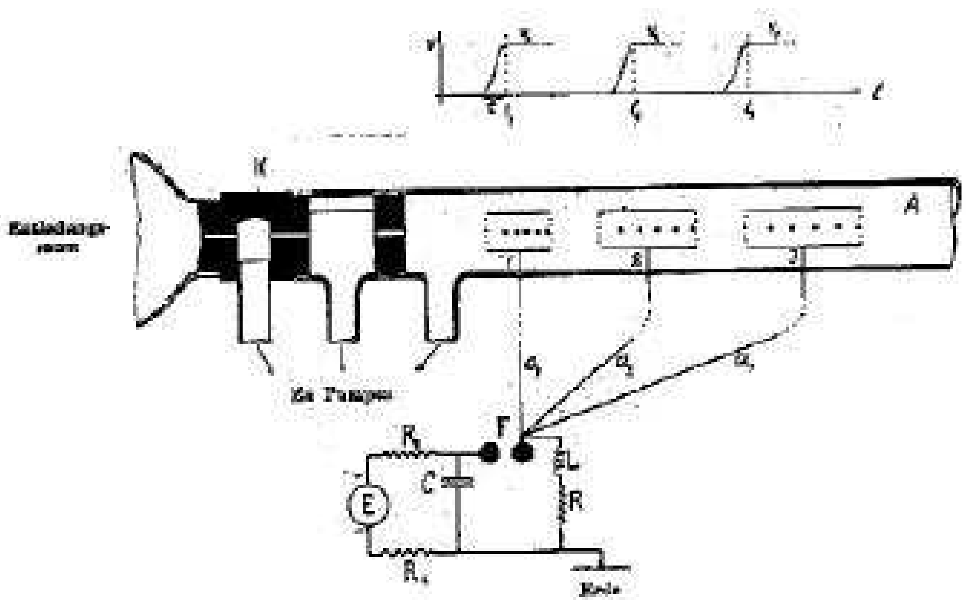
Ising linac

- 1924, Ising proposes the acceleration using a variable electric field between drift tubes (the father of the Linac).

- The potential wave is applied to the gaps via wires (a1, a2, a3...) with adjusted lengths to ensure synchronism.
A consequence: only works if velocity increases with time → non-relativistic regime.

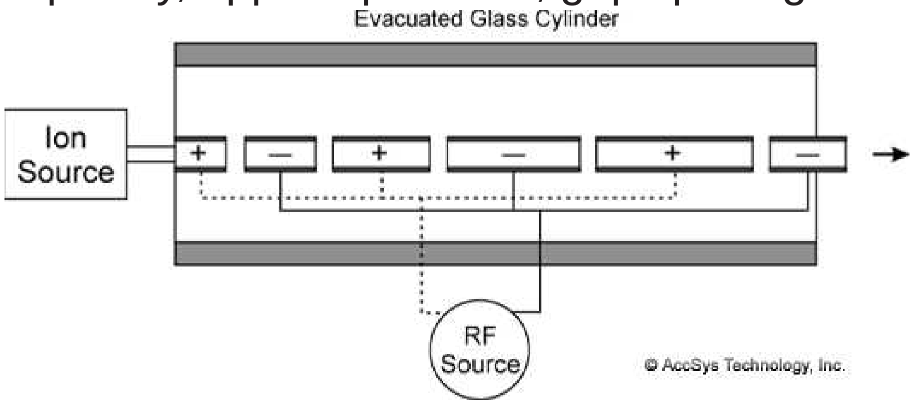
- Between gaps, particle bunchlets travel with constant velocity within drift tubes 1, 2, 3.

- It appeared not technologically possible to achieve a practical accelerator.
  - difficulty of spark excitation
  - inefficiency of wire transmission lines



Wideroe linac (1/3)

- 1928, Rolf Wideroe in Berlin first demonstrates resonant acceleration by applying Ising principle using a 1 MHz, 25 kV generator, connected to drift tubes forming a series of successive gaps.
- He succedes accelerating potassium ions in that structure, up to 50 keV,
- achieving the resonance required correlation between the various parameters : type of ion, RF frequency, applied potential, gap spacing.



- Drift tubes with increasing length are arranged along beam propagation axis
They act like Faraday cage : bunch inside tube feels no field

- They are applied $U(t) = U_0 \sin(\omega\, t)$. At a given time, potential alternates from one gap to the next ("π" mode accelerating structure)

- $U(t)$ causes accelerating (or decelerating) gradient between tubes during half a period

- After n gap, a particle at (constant) phase ϕ with the wave has $E_n = nqU_0 \sin\phi$

- Distance between gaps n and n+1 is (with v_n=velocity, T =RF period $= 2\pi/\lambda$)
$d_n = v_n T/2 = \beta_n \lambda/2$

- A straightforward, fundamental effect of this resonance method is "beam bunching".

Wideroe linac (2/3) : Sloan-Lawrence...

- Cyclotron was not the first step of E.O. Lawrence into resonant acceleration : see later on.
- With his student David Sloan in 1928, he built first a Wideroe linac accelerating Hg+ ions through a total of fifteen tubes.

  - Hg+ yields low β, hence reasonable drift length $\beta\lambda/2$, given low RF frequency available at that time (1 - 20 MHz)

  - They were able in 1931 to accelerate Hg^+ ions to an energy of 1.26 MeV, i.e. as if they had 1.3 million volts at their disposal, using 30 tubes, and 48 kV/10 MHz voltage.

  - That linac was lengthened and further developed for a few years.
- Not much happened until post-WWII times, problems remained to be solved :

  - transverse focusing was not ensured

  - stability of bunch-to-RF phase (ϕ) in long structures - phase stability had not yet been invented...

  - Wideroe structure was using long wavelength, yielding prohibitive drift tube length $l \approx \beta\lambda/2$ for high energies...

  - not only high frequency, also high power generators were not available (kWatts, to compensate antena-like losses in that antena-like device...

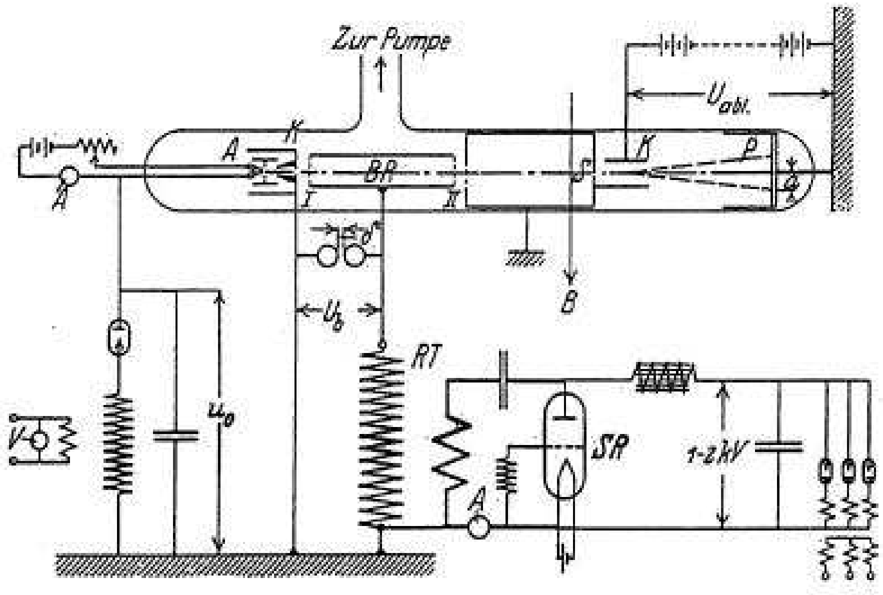
  - Cyclotron, developping in parallel, allowed high energies, in the 10 MeV proton range at that time, with small accelerator size.

Wideroe linac (3/3), exercise

Find length of the drift tube in Wideroe's experiment.

Wideroe's paper gives, 0.5cm gap, 20kV in the gap, $v_0 = 2.2\,10^7$cm/s, f=1MHz.

Potassium 1+ accelerated, Q/A$\sim$19/40.

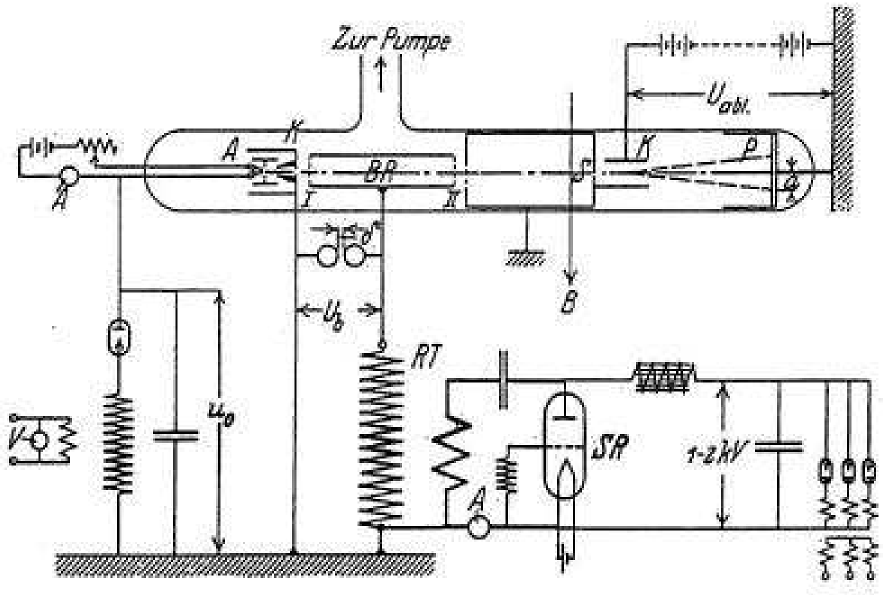


Wideroe linac (3/3), exercise

Find length of the drift tube in Wideroe's experiment.

Wideroe's paper gives, 0.5cm gap, 20kV in the gap, $v_0 = 2.2\,10^7$cm/s, f=1MHz.

Potassium 1+ accelerated, Q/A$\sim$19/40.

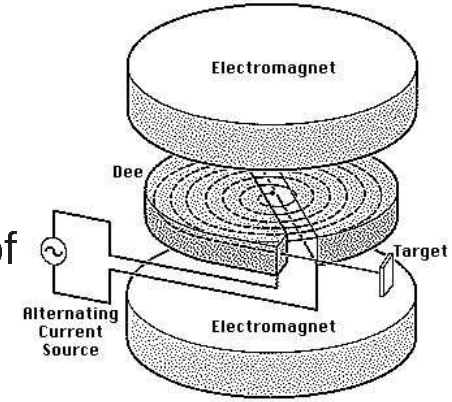


Resp. : distance between gap 1 and gap 2 is

$d_n = \beta \times \lambda/2 = v/c\ \times\ c/f\ /2 = 2.2e7/1e6/2 \approx 11$ cm

Hence tube length $\approx$ 10 cm.

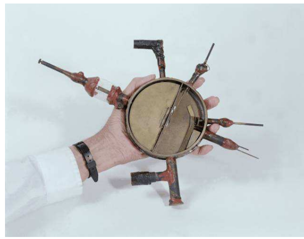
Cyclotron (1/5)

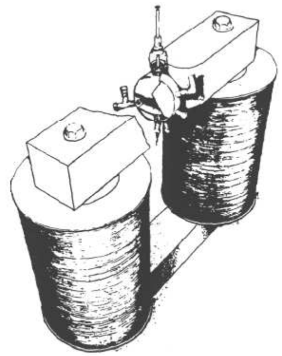


- 1929-1930, Ernest O. Lawrence inspired by Wideroe & Ising ideas invents (the principle of) the cyclotron :

  having read Wideroe's paper, he speculated on the use of a magnetic field to bring the particle back to a *single* accelerating gap next to acceleration.

  - Doing so he found that the revolution frequency in uniform B is constant : the "cyclotron angular frequency", $\boxed{\omega_0 = qB/m}$
  - That allows RF gap voltage at constant frequency, $f_{RF} = qB \,/\, 2\pi m$.



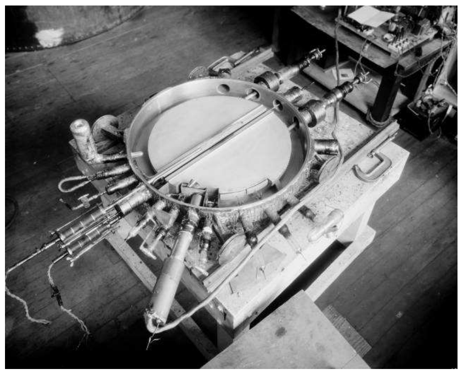


- 1931, Stanley Livingston, Berkeley, demonstration with 5-inch cyclotron by acceleration of hydrogen ions up to 80 KeV (about 40 turns up to $r \approx 4.5$ cm).

- 1932, ϕ30 cm cyclotron built by Lawrence produces protons at 1.25 MeV and breaks atoms *a few weeks after Cockcroft-Walton's Li + p*

- 1934, Berkeley, E.O. Lawrence builds a 27-inch cyclotron, accelerates protons to 3 MeV and D to 5 MeV

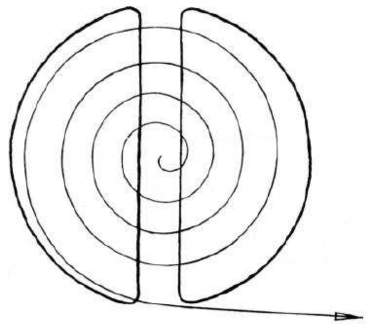
- 1939, E. O. Lawrence receives the Nobel Prize "for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements".



The device is inserted in the gap of an electromagnet.

- That was just the beginning of a lasting story, yet...

Cyclotron (2/5) - classical



With B constant in time and uniform in space, as particles gain energy from the rf system, they stay in synchronism, but spiral outward in r.

- Non-relativistic cyclotron

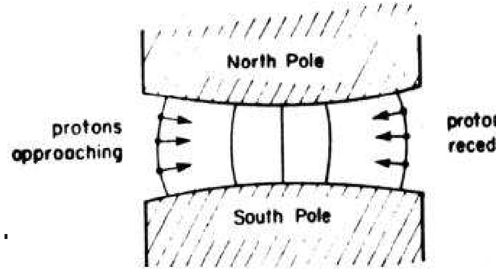
  - orbit : $\boxed{r = v/\omega_0 = mv/qB}$
  - focusing (1) :

    $F_z = qvB_r \approx qv\frac{\partial B_r}{\partial z} \equiv qv\frac{\partial B_z}{\partial r}$

    $\ddot{z} - \frac{qv}{m}\frac{\partial B_z}{\partial r} = 0 \rightarrow \omega_z^2/\omega_0^2 = \nu_z^2 = -\frac{r}{B_z}\frac{\partial B_z}{\partial r} = -k,$ $\quad \boxed{\nu_z = \sqrt{-k}}$.

    hence the field index k needs be negative : B_z **is slowly decreased with radius**.

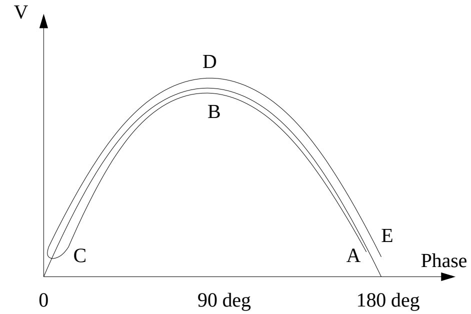
    Similarly, $\boxed{\nu_r = 1 + k}$. This sets the requirement $\boxed{-1 < k < 0}$



  - focusing (2) : is also ensured at lower energy by the electric field.
  - isochronism :

    The condition for vertical focusing, $-1 < k < 0$ (B is not constant), spoils the isochronism.

    As a consequence, the phase is not constant (ABCDE path)



  - bunching : particle beam injected into the cyclotron necessarily gets bunched, at the frequency of the RF (the time interval between two bunches is an RF period)

- The classical limit ($\gamma \approx 1$) is $\sim$25 MeV for protons, 50 MeV for D and α, (about $2-3$% increase in mass), GANIL in Caen accelerates Carbon to about 100 MeV/u...

- That was enough energy to transmute all nuclei... The classical cyclotron allowed discovering oodles of nuclear reactions and isotopes.

  Yet, let's keep in mind : transmutation was not the all story

Cyclotron (3/5) - classical

- Relativistic energies, the bad news :

  - The cyclotron resonance $\omega_0 = qB/\gamma m$, with $r = \beta c/\omega_0$ yields $\boxed{k = \frac{\beta}{\gamma}\frac{\partial\gamma}{\partial\beta} = \beta^2\gamma^2}$

  - so k cannot satisfy $\boxed{-1 < k < 0}$,

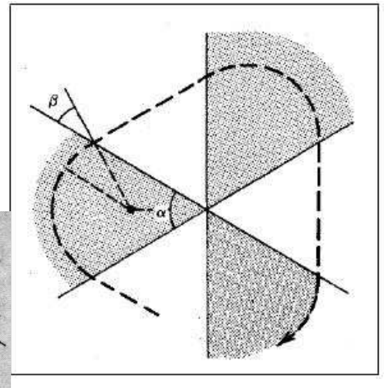
  isochronism requires that $B(r) \propto \gamma$, which yields vertical defocusing...

- That was the end of the story, ~ 25 MeV protons, etc... :
  Hans Bethe (1937) :
  "... it seems useless to build cyclotrons of larger proportions than the existing ones... an accelerating chamber of 37 cm radius will suffice to produce deuterons of 11 MeV energy which is the highest possible..."

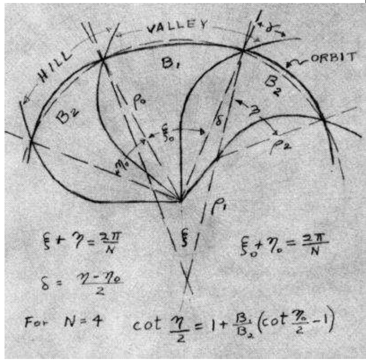
  Frank Cole : "If you went to graduate school in the 1940s, this inequality ($1 < k < 0$) was the end of the discussion of accelerator theory."

- Until...

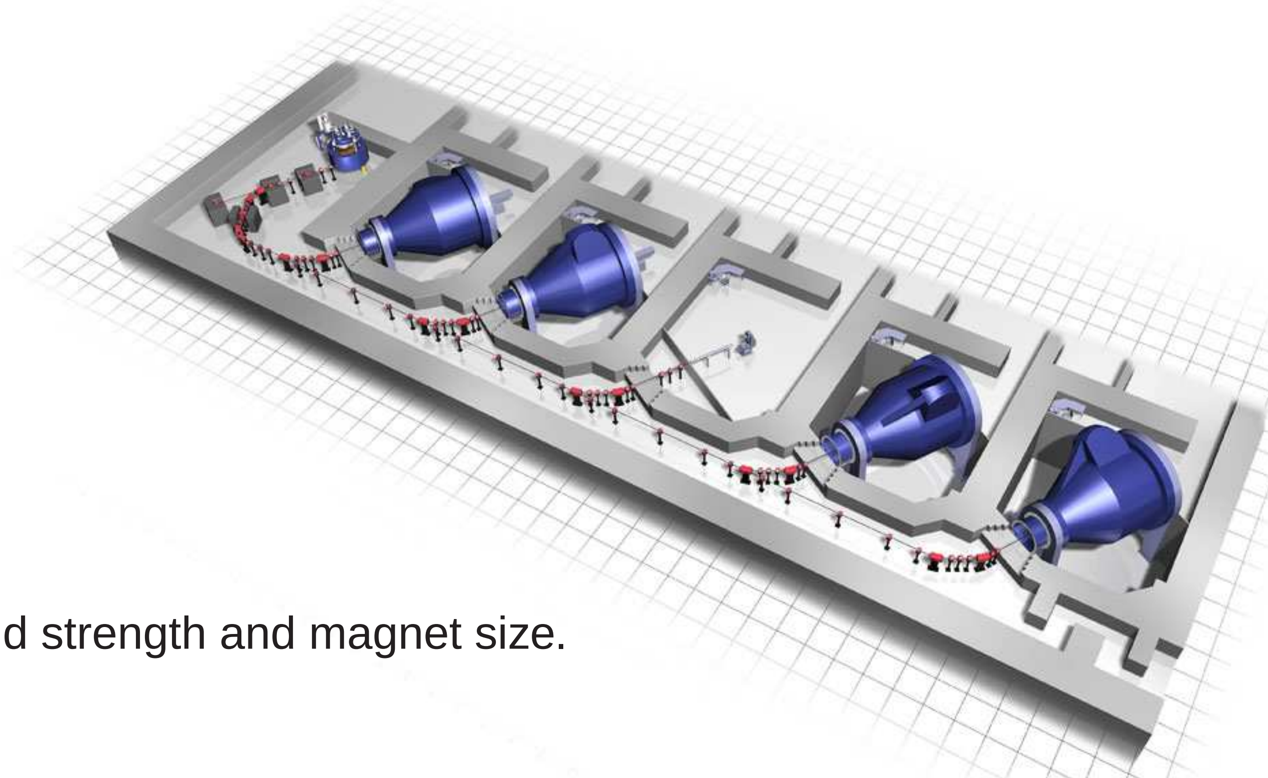
Cyclotron (4/5) - Thomas focusing



- 1938, L.H. Thomas, “The Paths of Ions in the Cyclotron”, introduces the “Thomas focusing”, based on separate sector bending, namely, “edge-focusing”,



- 1954, Kerst, spiral edges increase vertical focusing further
  $\boxed{\nu_z = \sqrt{-k + F^2(1 + 2\tan^2\xi)}}$, $\quad F = Flutter = \frac{<B^2> - <B>^2}{<B>^2}$
- That allowed having $B(r)$ increase in proportion to γ, so to ensure constant RF frequency ($\omega_0 = qB/\gamma m$), while *preserving vertical focusing*.
- Modern cyclotrons still rely on these principles



- Cyclotron is limited in energy by its field strength and magnet size.

Cyclotron (5/5), exercise

On RF harmonic 1, which RF frequency applied on dees is needed to accelerate a proton in a $\sim$uniform, 1 Tesla magnetic field ?

What is the energy gained by a proton when it reaches $r = 0.3$ m ?

Cyclotron (5/5), exercise

On RF harmonic 1, which RF frequency applied on dees is needed to accelerate a proton in a $\sim$uniform, 1 Tesla magnetic field ?

What is the energy gained by a proton when it reaches $r = 0.3\,$m ?

Answers :

1/ $f_{rev.} = eB/2\pi m = c^2B/2\pi(mc^2/e) = 9\,10^{16} \times 1/2\pi 10^9 \approx 15\,$MHz
Two accelerating gaps at 180 degrees $\Rightarrow f_{RF} = f_{rev.}$

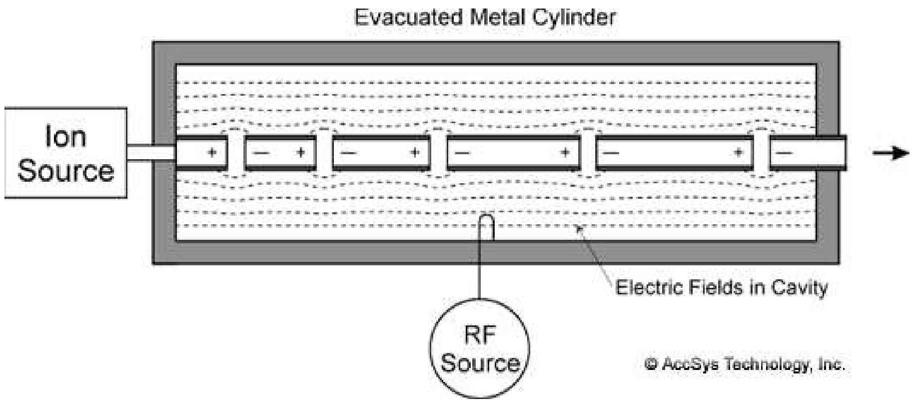
2/ From $r = \frac{mv}{eB}$ one gets $\frac{1}{2}mv^2 \equiv E = \frac{1}{2}\frac{(eBr)^2}{m} = \frac{1}{2}\frac{eB^2r^2c^2}{(mc^2/e}$ hence $\frac{E}{e}(eV) = \frac{1}{2}\frac{B^2r^2c^2}{(mc^2/e)}$
$\frac{E}{e}(eV) = \frac{1}{2}\frac{1^2(0.3)^2(3\,10^8)^2}{10^9} \approx 4.3\,$MeV.

Alvarez linac (1/2)

- The development of radar technology during WWII offered pulsed, *high power*, up to GHz RF generators ("magnetron", "klystron"), so allowing wavelengths in meter range (appropriate for ions $v/c < 1$) to cm range (electrons, $v \approx c$).
- 1946, L. Alvarez and coworkers at the Lawrence Berkeley Radiation Laboratory developed a proton linear accelerator based on injection of 200 MHz RF wave into a *resonant* metallic cylindrical cavity containing the wideroe-type drift tube arrangement.

  - the linac is injected with a 4 MeV electrostatic accelerator

  - protons are accelerated up to 32 MeV in the Alvarez structure



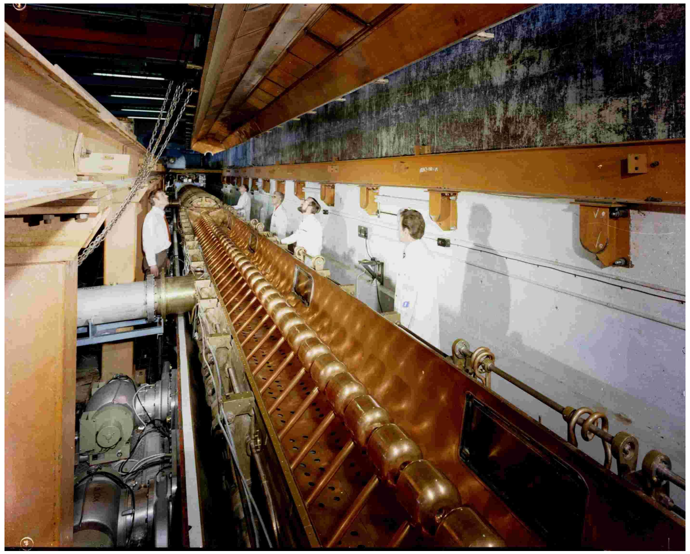
Remember, Wideroe's tubes were in a glass cylinder (strong antenna-like power losses), they were connected to an AC generator.

- Transverse focusing : ensured at gaps by grids shaping the (varying) E field.
- RF phasing : an accelerating standing wave fills the cavity. The particular resonant mode of interest (amongst oodles) is that with all gaps having the same polarity ("$\beta\lambda$" or "2π" accelerating mode)
- Evolutive geometry of the tubes (length & diameter) with distance causes cells to resonate on identical frequency.

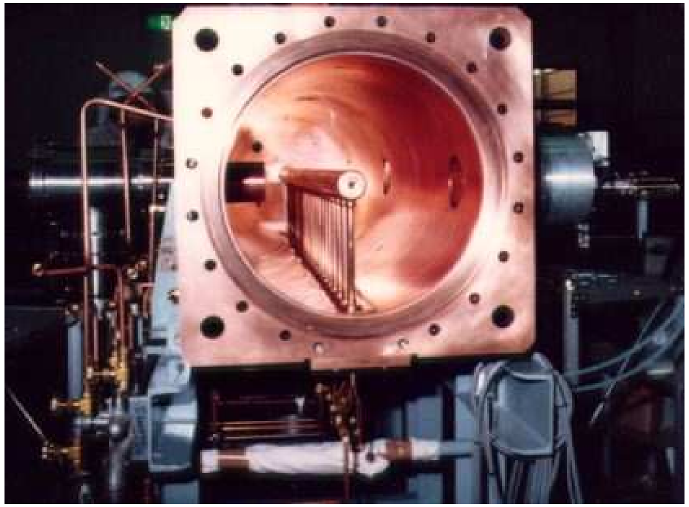
Alvarez linac (2/2)

• Later on longitudinal focusing (phase stability) would be invented, ensuring best transmission. Transverse focusing today ensured with quadrupoles located in the drift tubes.

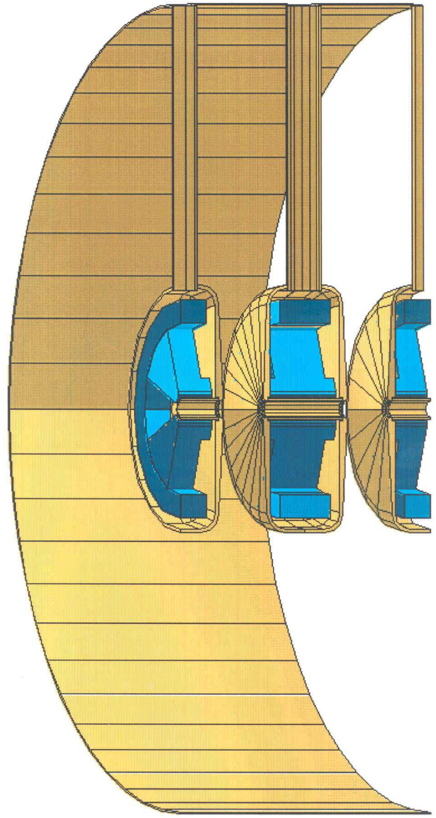
• DTLs are nowadays currently used as primary injection stages in hadron linac chains, or as injectors into synchrotrons.



202M Hz/70 MeV Alvarez injector linac at ISIS, RAL.



7 MeV Alvarez DTL, typical injector of medical synchrotron : pre-acceleration of protons or Carbons before injection into synchrotron.



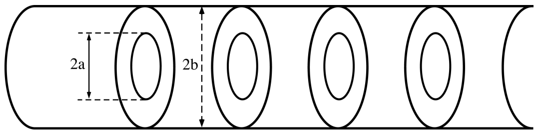
Quadrupoles in drift tubes.

Electron linacs (1/3)

- Following the development of high frequency, high power radar RF sources, the development of high energy (100-1000 MeV range) electron linacs as soon emerged. High frequencies (the so-called "S-band", $\sim$3 GHz and "L-band", $\sim$1.2 GHz radar frequencies) have been used.

- A particular direction of linac technology evolution was next the travelling wave structure, a waveguide type of structure (the drift tubes can be suppressed...)

  Disk loading inside the waveguide ("iris loaded waveguide") ensures phasing between varying-β electron and $v_\phi < c$ travelling wave



- In 1947 William W. Hansen, at Stanford University in California, constructed the first traveling-wave electron linear accelerator.

- A modern, compact, standing wave, 0.015 up to 5 MeV, electron linac structure. Typical of medical application (radio-therapy).

  Given the high RF frequency, the tank diameter is small. Given the very high gradient so achievable, the tank is short.

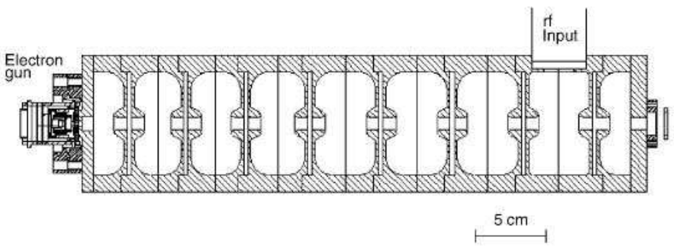
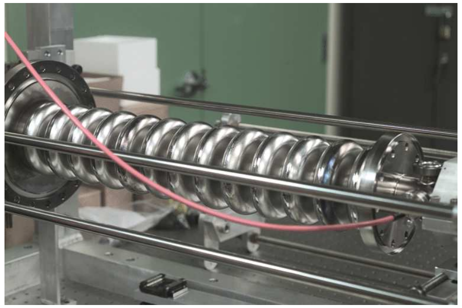


TABLE I. Accelerator parameters.

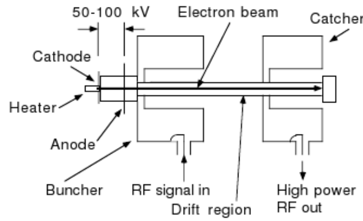
Energy (MeV)	3.5–5.5
Peak current (mA)	200
Repetition rate (Hz)	1–300
Pulse duration (μs)	3
Peak power (MW)	1
Average power (kW)	1
rf frequency (GHz)	2.997
Structure type	SWOAC
Operating mode	$\pi/2$
No. accelerating cavities	9
Magnetic lenses	NO
Length (cm)	40
Weight (kg)	25
Beam aperture size (mm)	12

Electron linacs (2/3)

Electron accelerating structures undergo a huge amount of R&D nowadays.



- 1.3 GHz SCRF cavity
  a technology typical of ILC type structure.
  Note : similar cavities, $\sim$100s MHz range, are developped for $\beta < 1$ accelerating structures (application in high power proton accelerators)



- The power RF wave is generated by “klystron amplifiers”...
- The largest linac is the 2-mile long 50 GeV accelerator at SLAC, Stanford, California, upgraded from the 1961’s 20 GeV installation.
  - in 1989, feeding the “Stanford Linear Collider” with e-(polarized), e+ beams, 90 GeV cm-Energy
  - today used for X-FEL R&D, plasma acceleration R&D ($\sim$GeV boost to 20 GeV electron beam...).

Electron linacs (3/3) - Acceleration, basics

The betatron (1/3)

- 1923 Wideroe invents the concept of betatron, a magnetic induction accelerator

  - 1927 He builds a model of betatron but fails - reported in his very 1928's paper on resonant linac acceleration.

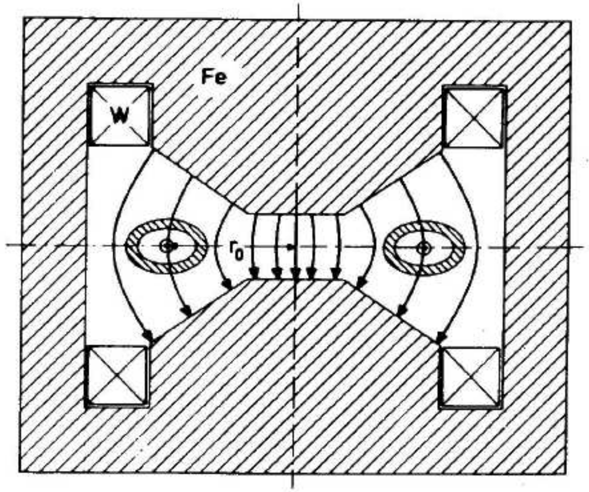
- 1940 Kerst builds and achieves operation of the first betatron, 2.2 MeV electrons

- In his 1941's paper, *"The acceleration of electrons by magnetic induction"*, D.W. Kerst establishes the theory of the transverse oscillatory motion of electrons around the reference orbit, known since then as the **"betatron motion"**.

Photo taken in 1966, Donald W. Kerst with the world's first e-betatron, built at the University of Illinois in 1940, and the 340 MeV world's largest betatron, built in 1950 for research.

- Similarly to cyclotron, betatron is limited in energy by its field strength and magnet size.

The betatron (2/3) - machine physics



- The 2-to-1, betatron rule rule (“Wideroe condition”, 1923)
  - the accelerating field B_a fills the central region of the gap
  - B_g is the guiding field along the orbit
  - $d\vec{p}/dt = F = q\vec{E}_a$ (see below) and $p = qB_g\rho$ yield

$$\boxed{B_g = B_a/2}$$

- Acceleration proceeds from induction :
  Magnetic fields varying for instance like $B(t) = \frac{1}{2}(1 - \cos(2\pi ft))$ (always > 0 !), $f \sim 50 - 200$ Hz, cause azimuthal/accelerating electric field :
  $\vec{rot}\vec{E}_a = -\partial\vec{B}_a/\partial t$ and $\int \vec{E}_a.\vec{dl} = \int\int \vec{rot}\vec{E}_a.\vec{ds}$ yield
  $2\pi\rho E_a = d\Phi/dt = \pi\rho^2 dB_a/dt$, $\boxed{E = \rho\dot{B}_a/2}$
- Focusing : gap shape causes B_g to decrease with r, to ensure axial stability.
- The betatron is insensitive to relativistic effects, that makes it propicious to acceleration of electrons.
- Today used for X-ray production for industry, radiography, injector in synchrotron light sources

The betatron (3/3) - exercise

Find the number of turns for acceleration cycle in a betatron

Parameters (University of Chiccago, Kerst, 1949) :
Orbit radius $\rho = 1.22$ m
Maximum guiding field $B_g = 9.2$ kG
Injection energy $80 - 135$ keV
repetition rate 6 Hz
(Note : magnet weight is 275 tons, injected current is 1-3 A.)

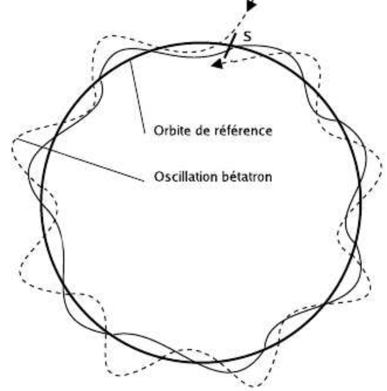
The betatron (3/3) - exercise

Find the number of turns for acceleration cycle in a betatron

Parameters (University of Chiccago, Kerst, 1949) :
Orbit radius $\rho = 1.22$ m
Maximum guiding field $B_g = 9.2$ kG
Injection energy $80 - 135$ keV
repetition rate 6 Hz
(Note : magnet weight is 275 tons, injected current is 1-3 A.)

Response :
Acceleration time $T \sim 1/$repetition rate ~ 200 ms
Maximum induction field is $B_a = 2B_g \approx 1.8$ Tesla
Rate of field rise : $\dot{B}_a = (B_{a,final} - B_{a,initial})/T \approx 1.8/0.2 \approx 10$ T/s
Accelerating field along orbit is $E = \rho\dot{B}_a/2$ (V/m)
Circumference is $C = 2\pi\rho$, voltage experienced over a turn is
$\Delta V = EC = \pi\rho^2\dot{B}_a \sim \pi \times 1.22^2 \times 10 \approx 50$ (V)
Hence, increase of energy to 315 MeV requires about 30 million turns (?).

Betatron motion - basics



- We consider a cylindrical frame $(\vec{u}_r, \vec{u}_\theta, \vec{u}_z)$,
  - particle position is defined by $\vec{s} = r\vec{u}_r + z\vec{u}_z$,
  - magnetic field is defined by $\vec{B} = B_r\vec{u}_r, B_\theta\vec{u}_\theta + B_z\vec{u}_z$.
  - The motion satisfies $m\frac{d^2\vec{s}}{dt^2} = q\vec{v} \times \vec{B}$.
  - We introduce a reference circle with radius ρ, and the distance x from the particle to that circle such that $x = r - \rho$.

In presence of a magnetic sector with constant gradient $\frac{dB}{dx}$, index $n = -\frac{\rho}{B}\frac{dB}{dx}$, such that $B(x) = B_0(1 - n\frac{x}{\rho})$ (the field is said “linear”)
and taking, amongst other approximations, arc length $s = vt$ with v constant, one gets the *uncoupled* linear equations of motion for each one of the two planes, H and V :
$\boxed{x'' + \frac{1-n}{\rho^2}x = \frac{1}{\rho}\frac{\Delta p}{p}, \quad z'' + \frac{n}{\rho^2}z = 0}$ or, in variable $\theta = s/\rho$, $\boxed{\frac{d^2x}{d\theta^2} + (1-n)x = \rho\frac{\Delta p}{p}, \quad \frac{d^2z}{d\theta^2} + nz = 0}$
with $*' = d*/ds$, $\Delta p = p - p_0$ and p_0 the reference momentum.

Weak focusing requires $\boxed{0 < n < 1}$, in order to obtain global focusing in both H and V planes.

Hence the differential equations above both have for solution an harmonic oscillation,
- the horizontal one with respect to the circle with radius $\rho + \Delta x$ with $\Delta x = \frac{\rho}{1-n}\frac{\Delta p}{p}$,
- the vertical one with respect to the median (field symmetry) plane,

$\boxed{x = \Delta x + \hat{x}cos(\nu_x\frac{s}{\rho} + \phi_x), \quad z = \hat{z}cos(\nu_z\frac{s}{\rho} + \phi_z)}$

with $\boxed{\nu_x = \sqrt{1-n}, \quad \nu_z = \sqrt{n}}$ the “betatron wave numbers”, number of oscillations per turn.
$\lambda_x = 2\pi\rho/\nu_x$ and $\lambda_z = 2\pi\rho/\nu_z$ are the betatron wavelengths.
Note the property, $\boxed{\nu_x^2 + \nu_z^2 = 1}$.

5 Phase stability - let's anticipate on "synchrotron motion"

• Assume a single (for simplification) RF cavity located in some drift in a ring, with frequency $\omega_{RF} = h\,\omega_{revolution}$

• The accelerating voltage across the gap of the RF cavity can be expressed as:
$V = \hat{V}\sin\int_0^t \omega_{RF}dt' = \hat{V}\sin\phi(t)$

• The "synchronous particle" (the one that follows the closed orbit with nominal energy) will allways experience the same RF phase when passing the RF gap, the "synchrotron phase" :
$\phi(t) = \phi_s$

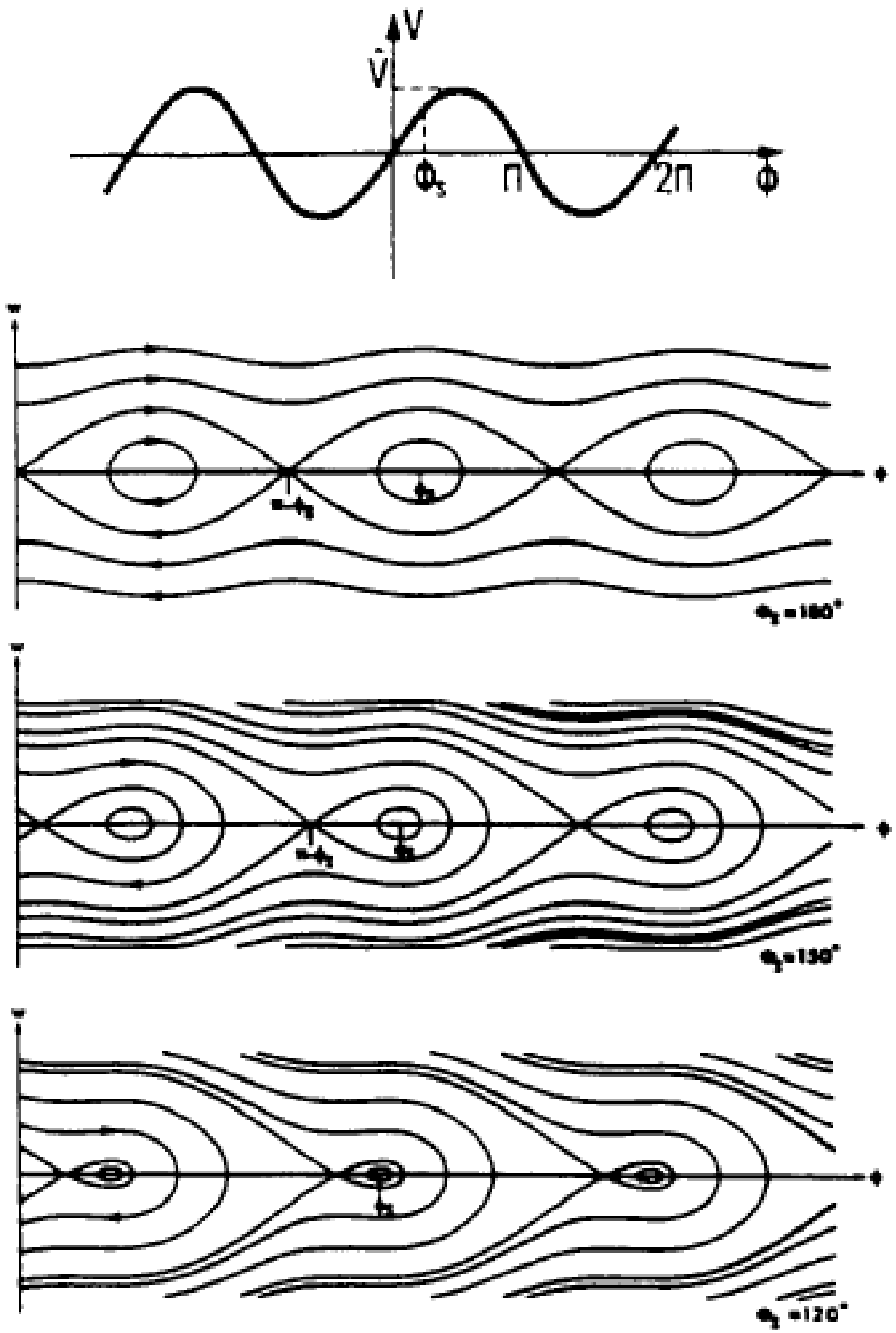
• and will experience energy gain
$\Delta W = q\hat{V}\sin\phi_s \equiv 2\pi q\rho R\dot{B}$

• A particle with arbitrary phase ϕ will satisfy

$$\boxed{\ddot{\phi} + \frac{\Omega_s^2}{\cos\phi_s}(\sin\phi - \sin\phi_s) = 0}$$

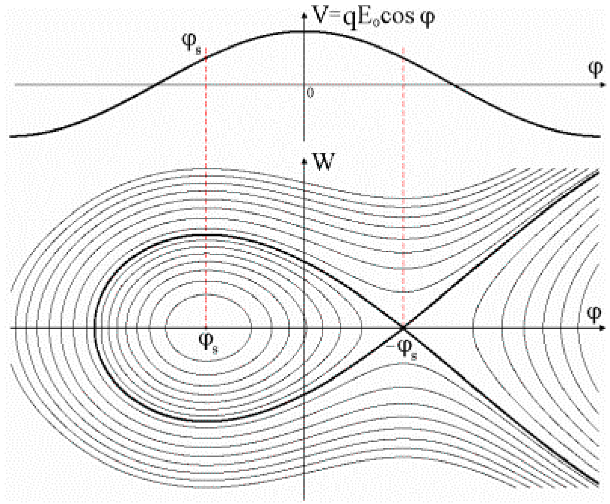
with $\Omega_s = (\frac{e\hat{V}h\eta\omega_s\cos\phi_s}{2\pi R_s p_s})^{1/2}$, $\eta = \frac{1}{\gamma^2} - \alpha$, $\alpha = \frac{dL/L}{dp/p}$

• If $\phi - \phi_s$ is very small, the motion in $(\phi, \dot{\phi})$ space is an ellipse.
The separatrix satisfies



Phase stability

• 1945 McMillan (California) and Veksler (USSR) independently propose synchronous acceleration with phase stability.
- both propose simple experimentation based on electron synchrotron (constant orbital/RF frequency).
- the guiding magnet is pulsed cyclically in synchronism with particle acceleration



• So... phase stability allows keeping particle bunch in resonance with the RF field, indefinitely...
- either by varying the RF frequency, for instance for particles with varying β - e.g., synchro-cyclotron, FFAG
- or by varying the guiding field, at $\sim$constant RF frequency (β $\sim$constant) - e.g. electron synchrotron
- or by varying both - e.g., proton synchrotron

• 1946, Richardson et al., Berkeley, report on synchro-cyclotron operation (constant field, varying RF frequency) of a converted cyclotron, thus demonstrating stability of synchronous orbits

• 1946, Goward and Barnes are first to make the synchrotron work in the UK (by adapting a betatron magnet)

- 1947, Pollock et al., operate a 70 MeV synchrotron at the GEC. Incidentally, *they observe for the first time the "synchrotron radiation", "a bright spot, visible in day light..."*
  - phase stable acceleration causes automatic compensation of synchrotron radiation energy loss...

- 1947 Oliphant and Hyde start a 1 GeV machine study in Birmingham, UK. The machine is built and operated in 1953, yet an American group overtakes them and is first with the 3 GeV Cosmotron at BNL, 1952.

- 1948 Berkeley, the first artificial mesons - pions - are created with a 380 MeV synchro-cyclotron

- The highest energy synchrotron-cyclotron, 720 MeV, was built in Berkeley in 1957.

  One of the highest energy proton synchro-cyclotron, 600 MeV, was started at CERN the same year
  - outer orbit radius 2.27 m
  - 2.5 m radius magnet poles
  - 2500 tons of steel
  - two 60 tons coils, each 750 kW

  Closed in 1990 after 33 years of nuclear physics.

Phase stability and the synchrotron, the start of the endeavor

• Synchrotron is the largest of the synchronous accelerators, and has produced the highest energies (Tevatron, LEP, LHC...)

- ring magnets are powered cyclically in synchronism with the RF frequency, yielding fixed (closed) orbit
- RF frequency follows revolution time while accelerating particle, in synchronism with magnetic field rise
- particles undergo "betatron motion" around closed orbit

• 1952, BNL, Livingston et al., first GeV range proton synchrotron, the Cosmotron, 3 GeV.

Unusally at that time, the Cosmotron has *four* straight sections, and *four* 90 degrees bending magnets.

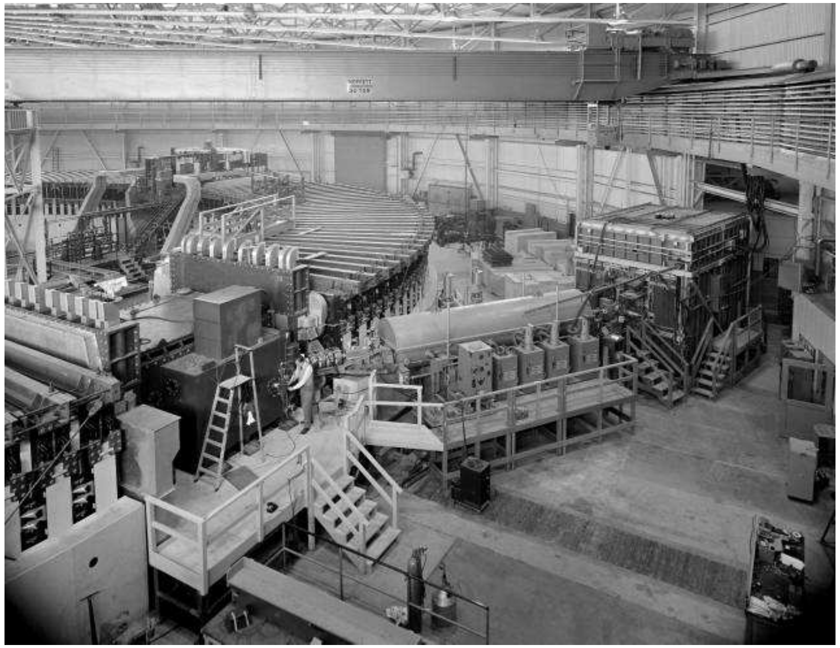
A step towards modern structures, each straight is devoted a particular function :

1: injection inflector

2, 3: respectively extraction deflector, extraction septum

4: RF station.

• 1954, LBNL, a Cockroft-Walton accelerator (right) feeds protons into an Alvarez linac (center) for 10 MeV injection into the 6.2 GeV, weak focusing, Bevatron synchrotron.



In spite of the discovery of strong focusing (*next chapter*), some labs carry on with construction of weak focusing synchrotrons...

• 1957, synchro-phasotron at Dubna, weak focusing - in spite of stron focusing discovered... - reached 10 GeV, proton

• ZGS at Argone, the highest energy weak focusing accelerator, 12 GeV : “zero-gradient focusing”, a variant of weak-focusing.
Focusing is ensured by angle of entrance and exit face of magnets, rather than $-1 < k < 0$

Allowed acceleration of polarized particles thanks to absence of depolarizing resonances in weak focusing structures.

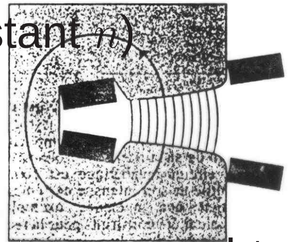
• SATURNE at Saclay, 1959, accelerates polarized ions

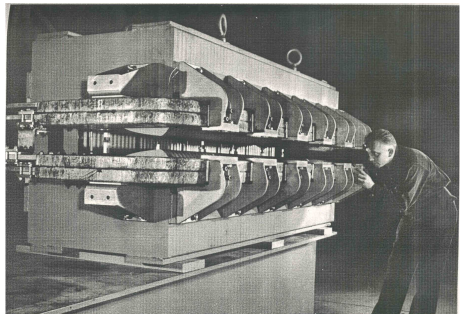
6 Strong focusing

• 1950 Christofilos, and 1952 independently Courant, Livingston and Snyder invent strong focusing.

• The alternating gradient optical structure (linac as well as ring) is based on a sequence of strong focusing magnets

- large index $\left|\frac{r}{B}\frac{dB}{dx}\right| >> 1$ (rather than the weak focusing $0 < n < 1$)
- alternating sign procuring overall focusing (instead of constant n),
- yielding large reduction of the transverse ("betatron") amplitude of particle motion

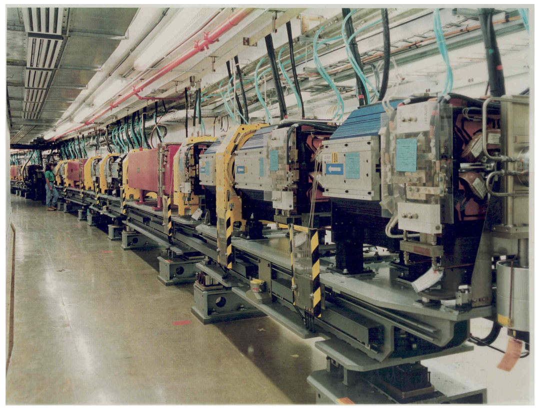




• A dramatic effect of the strong focusing is in the beam size, compared to weak focusing, yielding much smaller magnet aperture (cm's compared to 10s cm's), with big impact on magnet weight :

- Synchrophasotron, JINR, Dubna, USSR, 1957, Weak Focusing, 10 GeV, 36000 tons of steel (it is possible to ride a bicycle inside the vacuum chamber)
- CERN PS, 1959, Strong Focusing, 28 GeV, 3000 tons of steel

• A next idea is to separate the functions, "guiding" using pure dipole field magnets, and "focusing" using pure quadrupole field magnets



A straightforward consequence, the race to highest energies gains in speed...

- 1952, Courant, Livingston and Snyder propose a 30 GeV design, proton, based on this principle
- 1954, Cornell, 1.5 GeV electron ring
- 1958, CERN drops its design for a weak-focusing, 10 GeV FFAG in favour of a strong-focusing, 28 GeV synchrotron, completed 1959 : today's PS...
- 1960, BNL, operation of the 32 GeV AGS
- 1962, Cambridge (Massachussets), largest electron synchrotron, 6 GeV
- 1964, DESY, 7 GeV electron synchrotron
- 1967, Serpukhov, USSR, 76 GeV U70 proton synchrotron
- 1976, CERN, 450 GeV SPS, transformed to Sp$\bar{\text{p}}$S in 1982 thanks to stochastic cooling
- 1984, FermiLab, p$\bar{\text{p}}$ collider, cryogenic (4.2 Tesla), today 1 TeV$\times$1 TeV
- 1989, CERN, LEP e+ e- collider
- 1992, HERA at DESY, e(27.5GeV)-p(920GeV) collider, cm energy 318GeV, polarized leptons

etc...

Betatron motion basics - strong focusing

• Betatron motion of an on-momentum particle ($p = p_0$) in presence of alternating gradient strong focusing satisfies differential equations of the form - the Hill's equation :

$$\frac{d^2y}{ds^2} + K_y(s)y = 0 \qquad (y = x \text{ or } z)$$

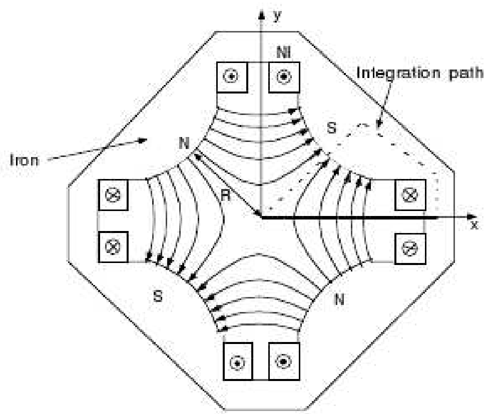
with $K_y(s+L) = K_y(s)$ periodic and L the period of the optical structure.

• The form of this equation is the same as in the weak focusing case, and $K_y = n_y/\rho^2$ with now index n_y large, $|n_y| >> 1$, alternatively positive or negative.

• In drifts, $K_y = 0$.

In quadrupole magnets, $K_y = \frac{1}{\rho}\frac{\partial B}{\partial x} = G/B\rho$ with G the "magnetic gradient", $B\rho = p/q$ the beam rigidity. K_y is called the "quadrupole strength".

From a technological viewpoint : in a quadrupole of a "separated function" optical structure (pure dipoles for guiding, pure quadrupoles for focusing), $G = B_{\text{pole tip}}/radius_{\text{pole tip}}$.



• Floquet's theorem allows establishing that y follows a pseudo-harmonic motion described by

$$y = \sqrt{\epsilon_y \beta_y(s)}\ \cos\left(\int \frac{ds}{\beta_y(s)} + \phi_y\right)$$

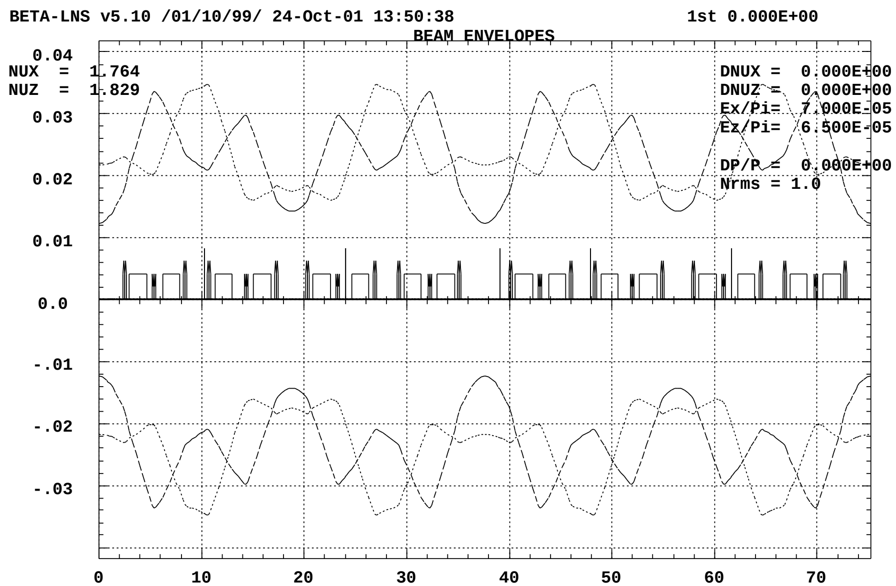
• The transverse motion is a pseudo-harmonic oscillation with frequency $\nu_y \times \omega_0$ ($\omega_0 = 2\pi/T_{rev.}$ is the revolution frequency around the ring) with

$\boxed{\nu_y = \frac{N\mu}{2\pi} = \frac{1}{2\pi}\int_s^{s+L} \frac{ds}{\beta_y(s)}}$ the "betatron wave number" per period.

ϵ_y and ϕ_y are constants of the motion that depend on initial conditions.

$\sqrt{\beta_y(s)}$ is the amplitude of the pseudo-harmonic oscillation.
$\lambda_y(s) = 2\pi\beta_y(s)$ is the local betatron wavelength.

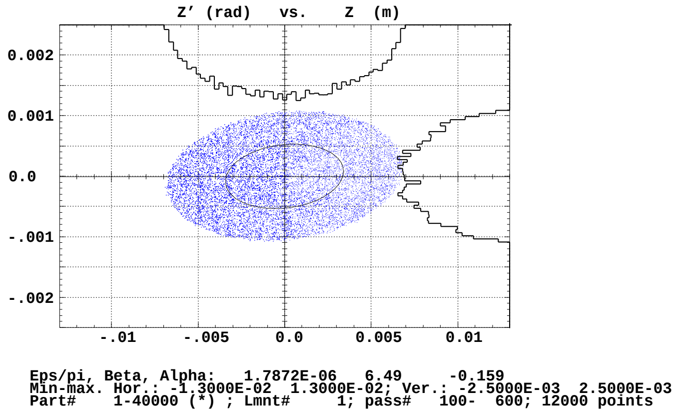
$\hat{y} = \sqrt{\epsilon_y \beta_y(s)}$ is the local maximum excursion of the motion.



• As a consequence, at given azimuth s, the particle motion leans on an ellipse with equation

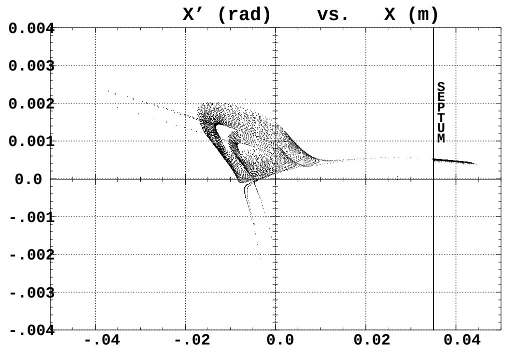
$$\gamma_y(s)y^2 + 2\alpha_y(s)yy' + \beta_y(s)y'^2 = \epsilon_y$$

with $\gamma_y = (1+\alpha_y^2)/\beta_y$, $\alpha_y = -\beta_y'/2$, $\epsilon_y =$(ellipse surface)/π.



• Further... : in presence of a quadratic - or “sextupole” - term in Hill’s equation (due to sextupole magnet in the ring),

$$\frac{d^2y}{ds^2} + K_y(s)y = a\,x^2$$



Allows beam extraction, “slow extraction”, typical of fixed-target physics.

Exercise

- Guess the size of a 3 GeV proton synchrotron

- Of a 1 TeV synchrotron with 4 Tesla SC dipoles

- Of a 7 TeV synchrotron with 8 Tesla SC dipoles

- How many turns does that take to accelerate from 50 MeV injection in a 3 GeV synchrotron ?

Exercise

- Guess the size of a 3 GeV proton synchrotron

  Response :

  $B\rho = \sqrt{T(T+2M)}/c \approx \sqrt{3(3+2\times 1)}/c \approx 4\,10^9(eV)/3\,10^8 \approx 12.3$ T.m

  $B \approx 1.8\,T \quad \Rightarrow \rho = B\rho/B \approx 6.8$ meters, hence magnetic length $2\pi\rho \approx 45$ m

  Assume packing factor ~ 0.4, hence geometrical radius$\sim \rho/.4 \approx 17$ m, $\boxed{\text{circumference} \approx 107 \text{ meters}}$

- Of a 1 TeV synchrotron with 4 Tesla SC dipoles

- Of a 7 TeV synchrotron with 8 Tesla SC dipoles

- How many turns does that take to accelerate from 50 MeV injection in a 3 GeV synchrotron ?

Exercise

- Guess the size of a 3 GeV proton synchrotron

  Response :

  $B\rho = \sqrt{T(T+2M)}/c \approx \sqrt{3(3+2\times 1)}/c \approx 4\,10^9(eV)/3\,10^8 \approx 12.3$ T.m

  $B \approx 1.8\,T \quad \Rightarrow \rho = B\rho/B \approx 6.8$ meters, hence magnetic length $2\pi\rho \approx 45$ m

  Assume packing factor ~ 0.4, hence geometrical radius$\sim \rho/.4 \approx 17$ m, $\boxed{\text{circumference} \approx 107 \text{ meters}}$

- Of a 1 TeV synchrotron with 4 Tesla SC dipoles

  $B\rho = \sqrt{T(T+2M)}/c \approx 10^{12}(eV)/3\,10^8 \approx 3300$ T.m, about 300 times the above

  Magnetic field is a bout 2.2 times the above. Assume packing factor 0.8 (the ring is mostly arcs + some RF + some beam services...)

  Hence length is ~300/2.2*(0.4/0.8) $\sim 70\times$the above, $\boxed{\approx 7 \text{ km}}$ (cf. Tevatron at FermiLab, B=4.2 T, 6.3 km)

- Of a 7 TeV synchrotron with 8 Tesla SC dipoles

- How many turns does that take to accelerate from 50 MeV injection in a 3 GeV synchrotron ?

Exercise

- Guess the size of a 3 GeV proton synchrotron

  Response :

  $B\rho = \sqrt{T(T+2M)}/c \approx \sqrt{3(3+2\times 1)}/c \approx 4\,10^9(eV)/3\,10^8 \approx 12.3$ T.m

  $B \approx 1.8\,T \quad \Rightarrow \rho = B\rho/B \approx 6.8$ meters, hence magnetic length $2\pi\rho \approx 45$ m

  Assume packing factor ~ 0.4, hence geometrical radius$\sim \rho/.4 \approx 17$ m, $\boxed{\text{circumference} \approx 107 \text{ meters}}$

- Of a 1 TeV synchrotron with 4 Tesla SC dipoles

  $B\rho = \sqrt{T(T+2M)}/c \approx 10^{12}(eV)/3\,10^8 \approx 3300$ T.m, about 300 times the above

  Magnetic field is a bout 2.2 times the above. Assume packing factor 0.8 (the ring is mostly arcs + some RF + some beam services...)

  Hence length is ~300/2.2*(0.4/0.8) $\sim 70\times$the above, $\boxed{\approx 7 \text{ km}}$ (cf. Tevatron at FermiLab, B=4.2 T, 6.3 km)

- Of a 7 TeV synchrotron with 8 Tesla SC dipoles

  7 times the above for $B\rho$ value, twice less for field value, i.e. $\boxed{\approx 25 \text{ km}}$ (cf. LHC, 27 km)

- How many turns does that take to accelerate from 50 MeV injection in a 3 GeV synchrotron ?

Exercise

- Guess the size of a 3 GeV proton synchrotron

  Response :

  $B\rho = \sqrt{T(T+2M)}/c \approx \sqrt{3(3+2\times 1)}/c \approx 4\,10^9(eV)/3\,10^8 \approx 12.3$ T.m

  $B \approx 1.8\,T \quad \Rightarrow \rho = B\rho/B \approx 6.8$ meters, hence magnetic length $2\pi\rho \approx 45$ m

  Assume packing factor ~ 0.4, hence geometrical radius$\sim \rho/.4 \approx 17$ m, $\boxed{\text{circumference} \approx 107 \text{ meters}}$

- Of a 1 TeV synchrotron with 4 Tesla SC dipoles

  $B\rho = \sqrt{T(T+2M)}/c \approx 10^{12}(eV)/3\,10^8 \approx 3300$ T.m, about 300 times the above

  Magnetic field is a bout 2.2 times the above. Assume packing factor 0.8 (the ring is mostly arcs + some RF + some beam services...)

  Hence length is ∼300/2.2*(0.4/0.8) $\sim 70\times$the above, $\boxed{\approx 7 \text{ km}}$ (cf. Tevatron at FermiLab, B=4.2 T, 6.3 km)

- Of a 7 TeV synchrotron with 8 Tesla SC dipoles

  7 times the above for $B\rho$ value, twice less for field value, i.e. $\boxed{\approx 25 \text{ km}}$ (cf. LHC, 27 km)

- How many turns does that take to accelerate from 50 MeV injection in a 3 GeV synchrotron ?

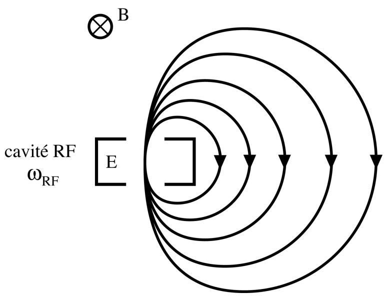
  Assume a single 10 kV peak RF station, somewhere in the ring

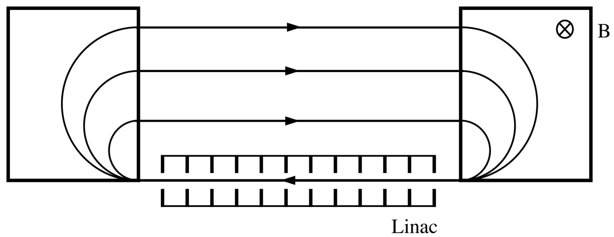
  Assume working RF phase is 30 degrees, hence energy gain per turn for the synchronous particle is 10 keV×sin(30deg) = 5 kV

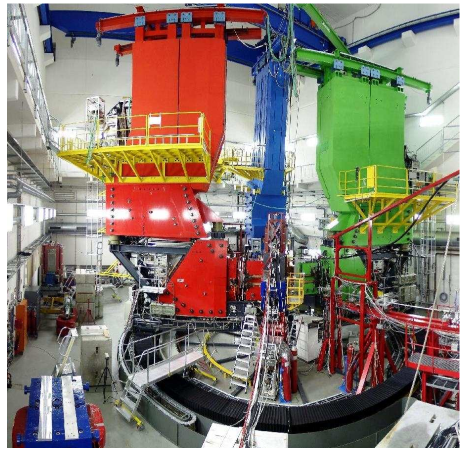
  Number of turns is $\sim 3\,10^9(eV)/5\,10^3(eV/turn)$ $\boxed{\approx 600000 \text{ turns}}$... Resonance phenomena are definitely a concern

7 More history...

- 1946, Richardson et al., Berkeley, report on synchro-cyclotron operation (constant field, varying RF frequency) of a converted cyclotron, thus demonstrating stability of synchronous orbits
  - Synchrocyclotrons have reached ∼700 MeV energy (CERN, USSR ...)
  - Like cyclotron, the limit is the magnet size
- 1954, Veksler invents the microtron







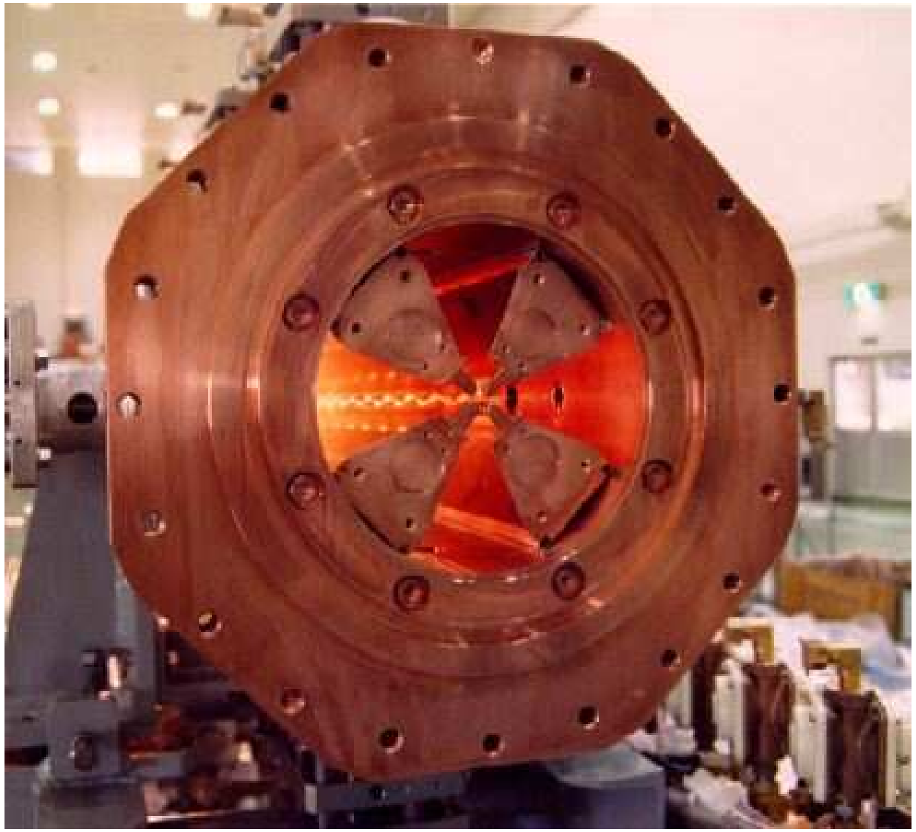
Mainz microtron,
MAMI, today

The energy gain is such that the path length is always an integer multiple of the RF wavelength
Since energy gain is very large, the concept essentially holds for electrons

- 1966, Budker and Skrinsky propose electron cooling (cf LEAR, CERN, Pb ions for LHC)
- 1970, Kapchinski & Teplyakov propose the RFQ (radiofrequency quadrupole).
- 1999, C. Johnstone, FermiLab, invention of the “non-scaling” FFAG for fast acceleration of muons for the neutrino factory / muon collider
- 1999, Fixed field acceleration of protons (KEK), demonstrator for various applications and for fast acceleration of muons in the neutrino factory

8 More accelerators

RFQ



Radio-frequency quadrupole ("RFQ"):

• A long electric quadrupole, with a sinusoidally varying voltage on its electrodes. The electrode tips are modulated in the longitudinal direction; this modulation results in a longitudinal field, which accelerates particles.

• It is a capable of a few MeV of acceleration. Typically used between the ion source and the Alvarez linac in proton RF linacs.

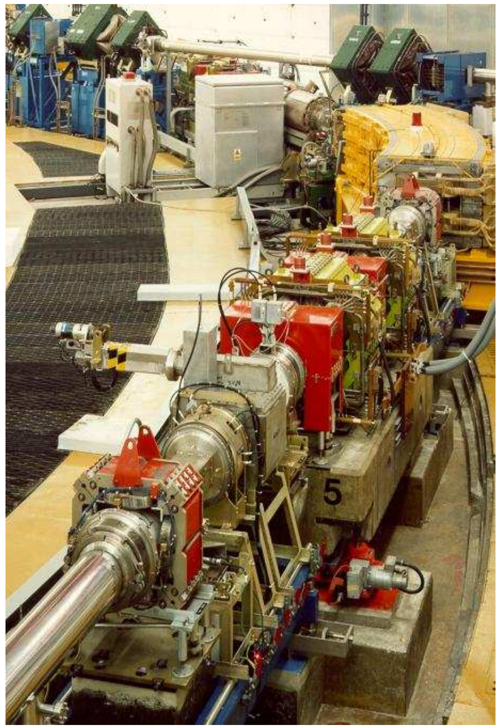
HPPA

Some examples of equipments addressed in this lecture :

SNS (1.2GeV/1.4MW/60Hz) :
source (H-, 2.5MeV) +
linac (1 GeV, DTL+CCL/200MeV + SCL/Nb-2K) +
ring : accumulator/buncher (1200turns/1μs pulse) +
Liq.Hg target

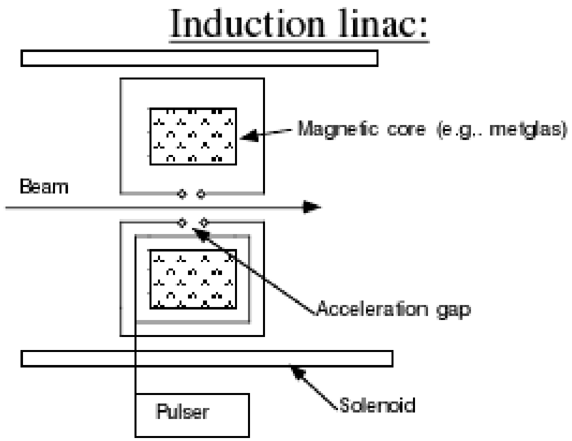
ISIS (800MeV/120kW/50Hz) :
source (H-, 35keV) +
linac (70MeV, DTL) +
ring : accumulator(130turns)/accelerator/buncher(2$\times$100 ns) +
target stations

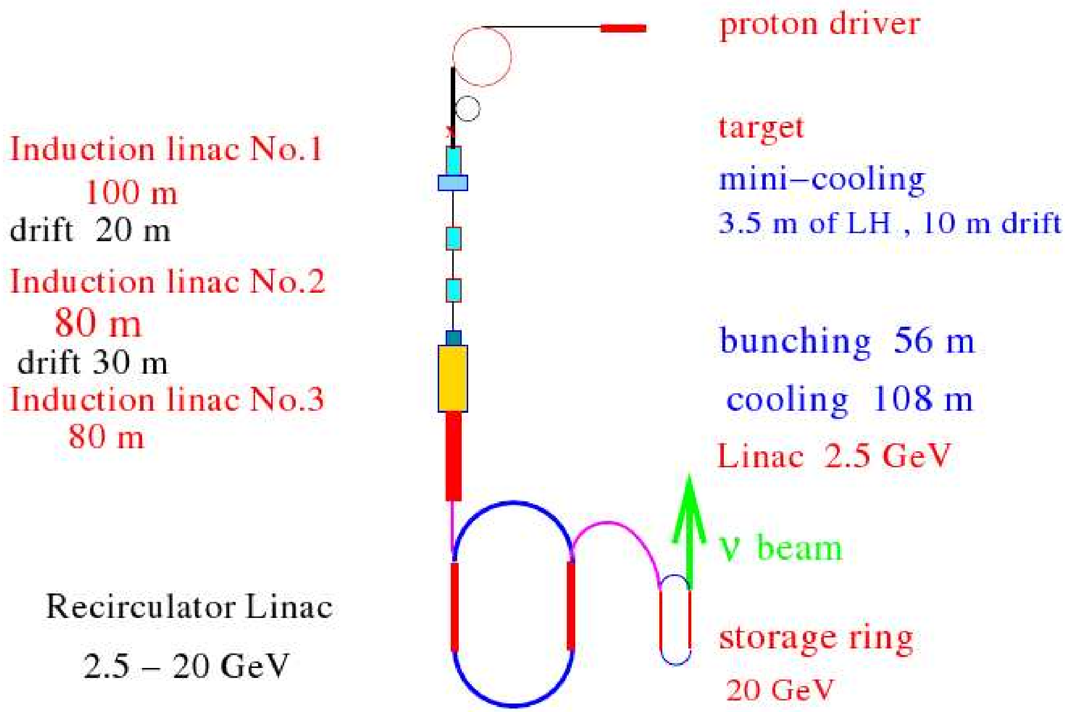
Target station at ISIS



ISIS 800 MeV ring

Induction linac





The beam forms the secondary circuit of a high-current pulse transformer.

Induction linacs have very low rep rates (a few Hz) and intermediate voltages (30-50 MV) but very high peak currents (>10 kA) in short (100 ns-1 s) pulses

- Example : an earlier method of non-distorting muon beam phase rotation in the neutrino factory :

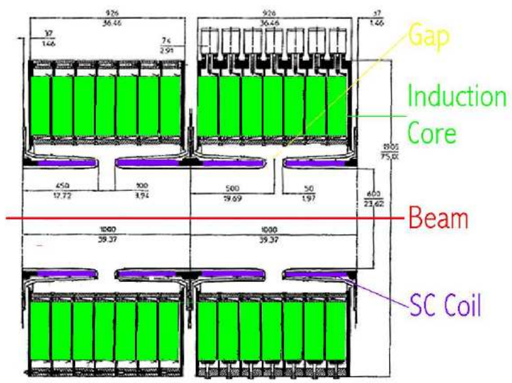


Figure 4.6: Cross section of two induction units.

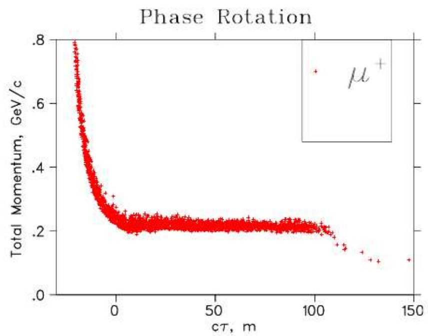


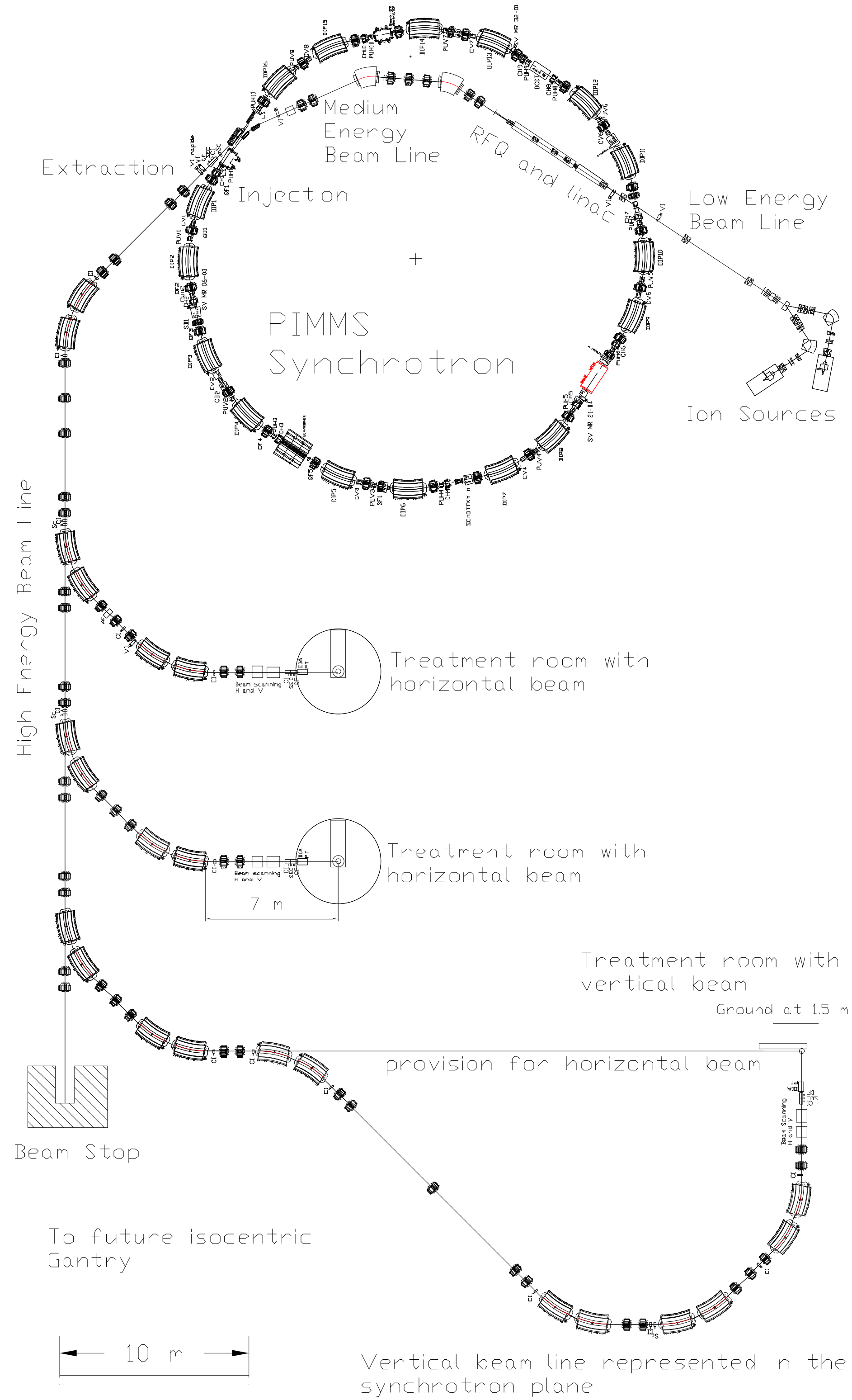
Figure 4.2: Beam longitudinal profile with non-distorting phase rotation.

Production of RIBs

See SPIRAL 2 at Caen, FAIR at GSI, for instance

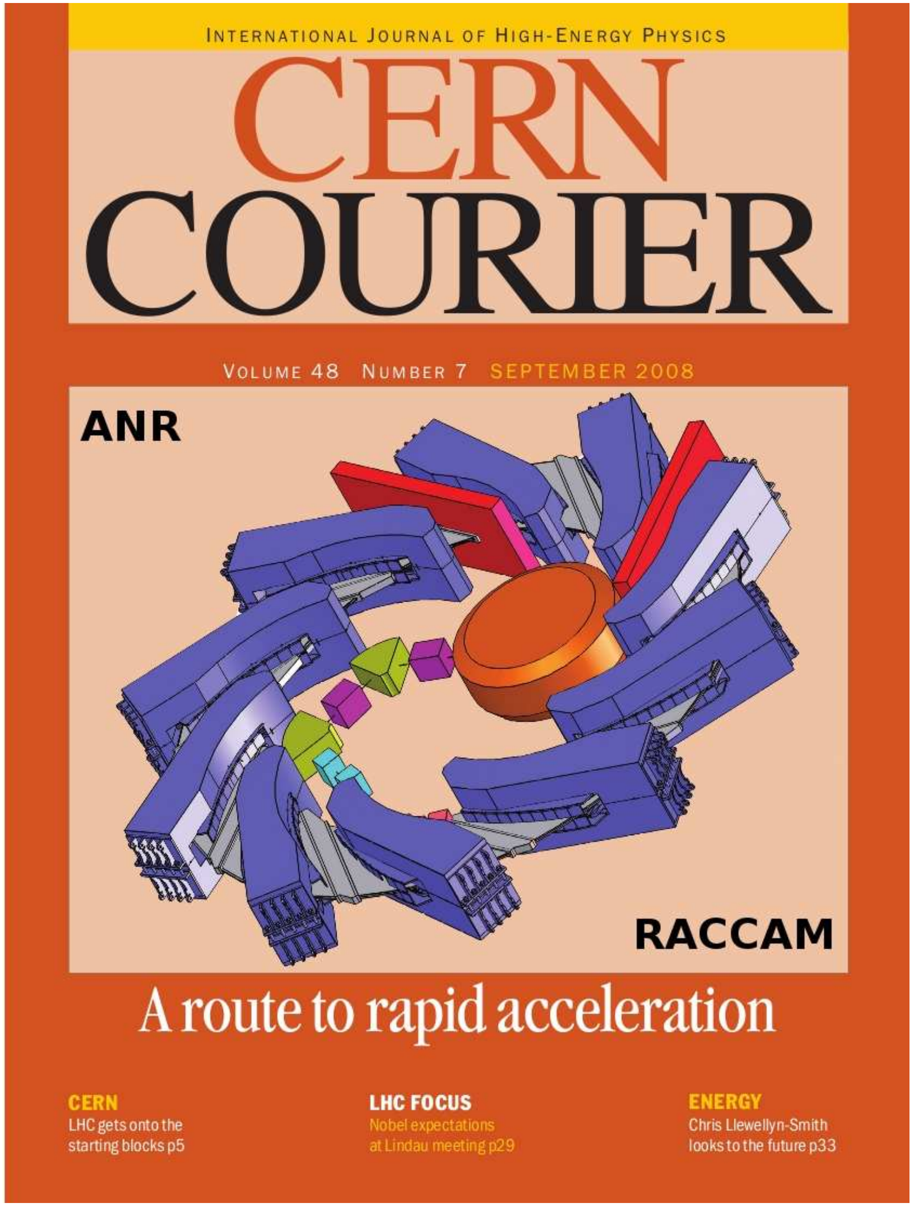
Medical machines

PIMMS Carbon-therapy synchrotron.



Medical machines

FFAG's : the RACCAM ANR project, 2006 - 2009



Light sources

• 1947, Pollock et al., operate a 70 MeV synchrotron at the GEC. Incidentally, *they observe for the first time the "synchrotron radiation", "a bright spot, visible in day light..."*

Ring LS

2nd generation light sources

Operational 2nd Generation Light Sources

	Energy (GeV)	Horizontal Emittance (nm-rad)	Vertical Emittance (pm-rad)	σ_x (μm)	σ_y (μm)	Top-up
PF-AR	5-6.5	160-295				
NSLS X-ray	2.8	75	150	300	6	no
KEK-PF	2.5	35.8				
ANKA	2.5	80	-			
NSRRC (Taiwan)	1.5	25.6	-			planned
NSRL (Hefei)	0.8	134, 27 planned				
NSLS VUV	0.8	160	> 350	1240	45	no
SSLS (Singapore)						
Super ACO	0.8	6.3 / 18	6.3E3/ 18E3	165 /389	191/ 387	-

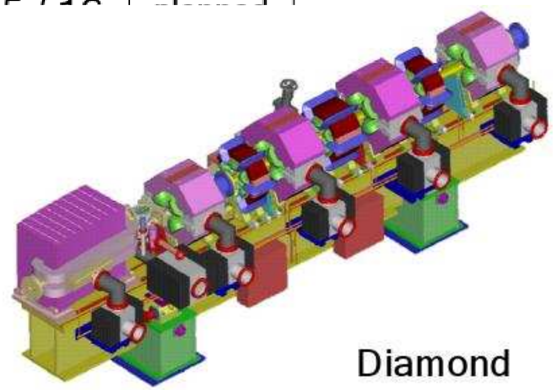
3rd generation light sources : $\epsilon < 20$ nm.rad

- Light sources are at a very mature level
- Sub-micron beam stability for new sources is expected, and achieved
- 100 nanoradian pointing stability requirements are on the horizon
- The technology is improving

Operational 3rd Generation Light Source* Parameters

	Energy (GeV)	Horizontal Emittance (nm-rad)	Vertical Emittance (pm-rad)	σ_x (μm)	σ_y (μm)	Top-up
SPring-8	8	6	14	390	7.5	yes
APS	7	2.5	25	271	9.7	yes
ESRF	6	4.0	30	380	14	studied
SPEAR-3	3	12 / 18	60 / 90	350 / 430	25 / 31	planned
CLS	2.9	15	200	326	30	planned
Pohang LS	2.0 / 2.5	12.1 / 18.9	12 / 19	350 / 434	22 / 27	no
SLS	2.4	5	40	86	6	yes
ELETTRA	2 / 2.4	7 / 9.7	< 70 / 97	241 / 283	[illegible]	[illegible]
ALS	1.5 / 1.9	4.2 / 6.75	200 / 150	240 / 310	[illegible]	[illegible]
BESSY-II	1.72	6	180-240	290 / 76	[illegible]	[illegible]

* $\varepsilon < 20$ nm-rad



Diamond

ALBA 3 GeV 4 nm.rad

4th GLS

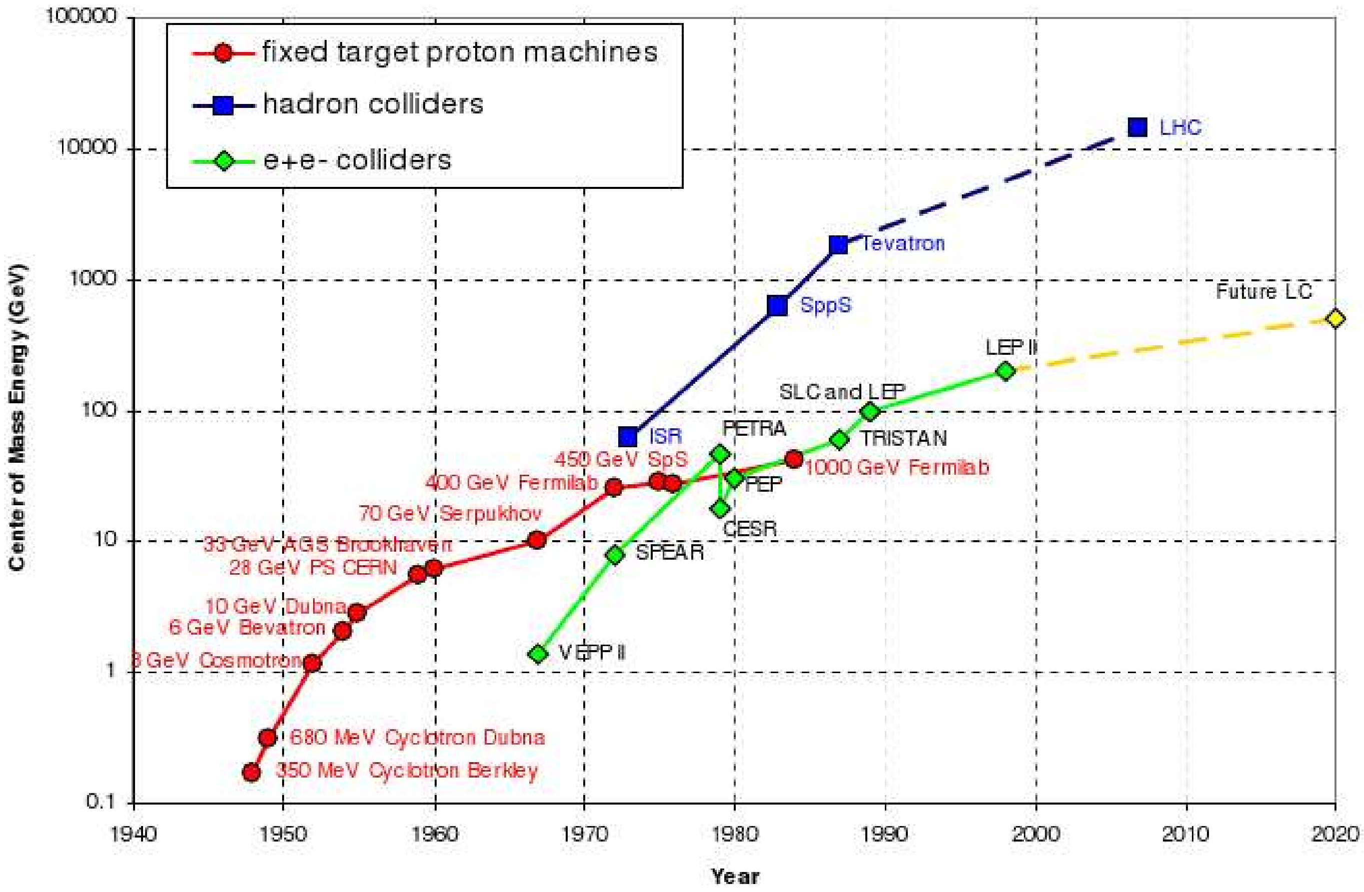
Typically, XFEL at DESY : SASE radiation, extreme brightness at $\sim$UV-VUV wavelengths

Innovations as “Energy Recovery RLA”, confer J-Lab RLA, and also $\sim$50 MeV ER-FEL experiments there

9 Colliders

Introduction

• The interest for colliders resides in the center-of-mass (CM) energy achievable compared with fixed target accelerators.



• The CM energy available in a collision between two particles, (1), (2), writes

$$E_{CM} = \sqrt{M_1^2 + M_2^2 + 2M_1 M_2 \gamma_1 \gamma_2 (1 - \beta_1 \beta_2)}$$

- Considering particles with the same mass M, in fixed target collision mode, incoming beam with energy E, one gets

$$E_{CM} \approx \sqrt{2ME}$$

The energy available goes as the square root of the accelerator energy

- Considering particles with the same mass M, in collider mode, beams with respective energies E_1, E_2, head-on collision, one gets

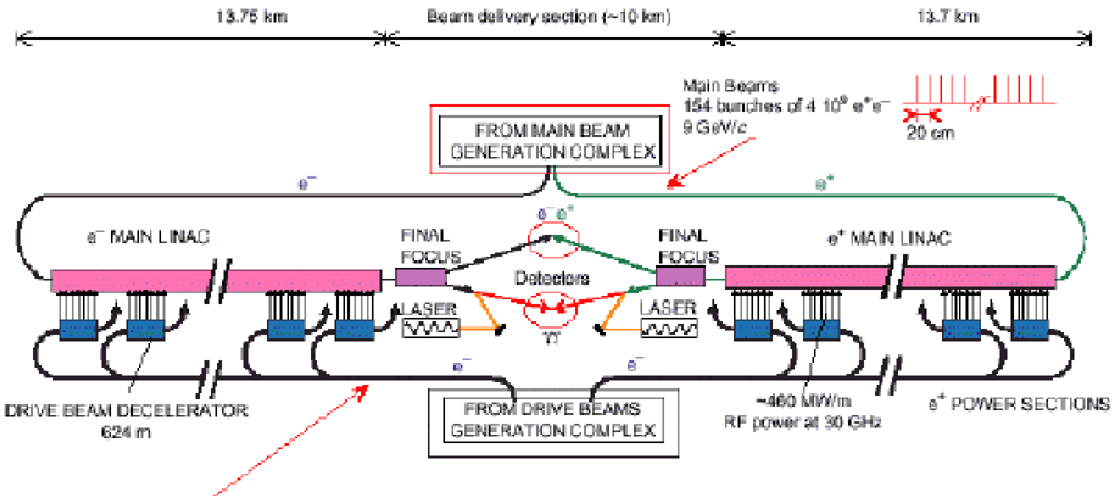
$$E_{CM} \approx 2\sqrt{E_1 E_2}$$

• For instance, if one whishes $E_{CM} = 14$ TeV, protons, that means,

- either E1 = E2 = 7 TeV with a collider
- or $\sqrt{2ME} = 14$ TeV, i.e. $E = 14^2 \,/\, 2M$ TeV with $M = 10^{-3}$TeV, yielding $E = 100$ PeV

• A dramatic consequence is that fixed target accelerators have disappeared from the race to higher energies.

• The largest electron ring collider was LEP, and there is no plan for higher energy elctron collider ring. The next generation linear collider (probably the next collider beyond LHC) will be a linac, ILC or CLIC type - to be decided in the 2010's.



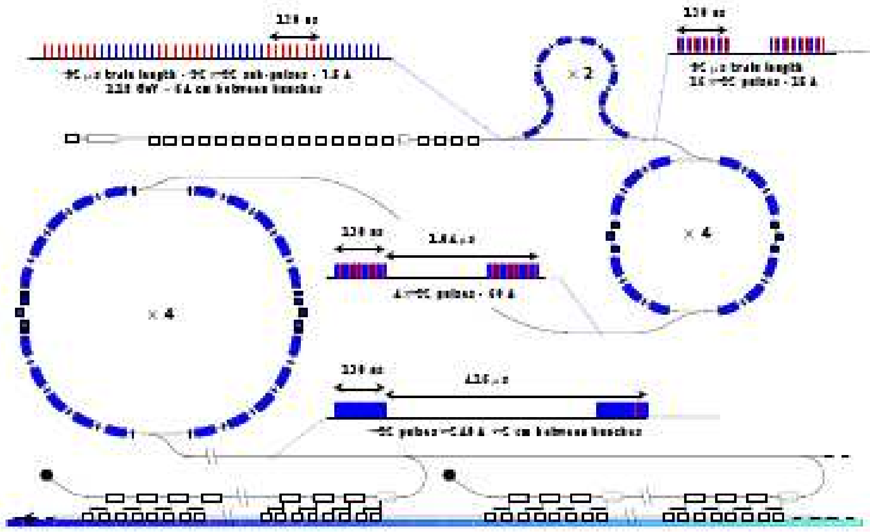
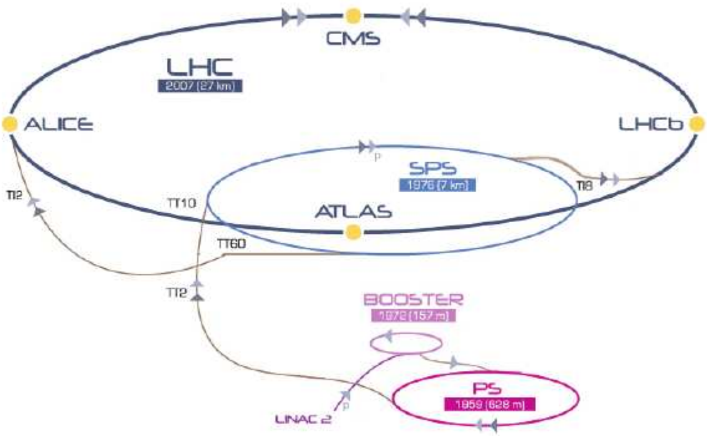
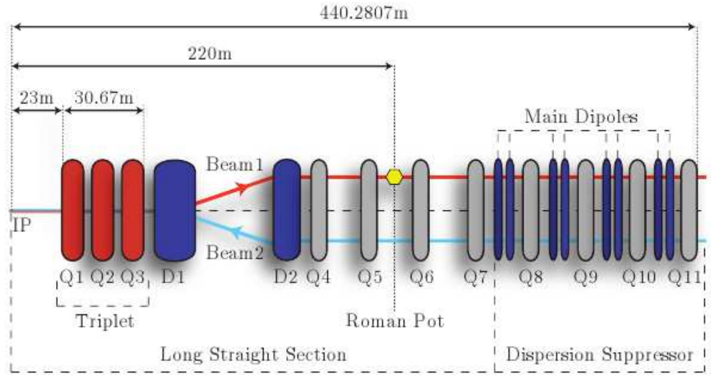
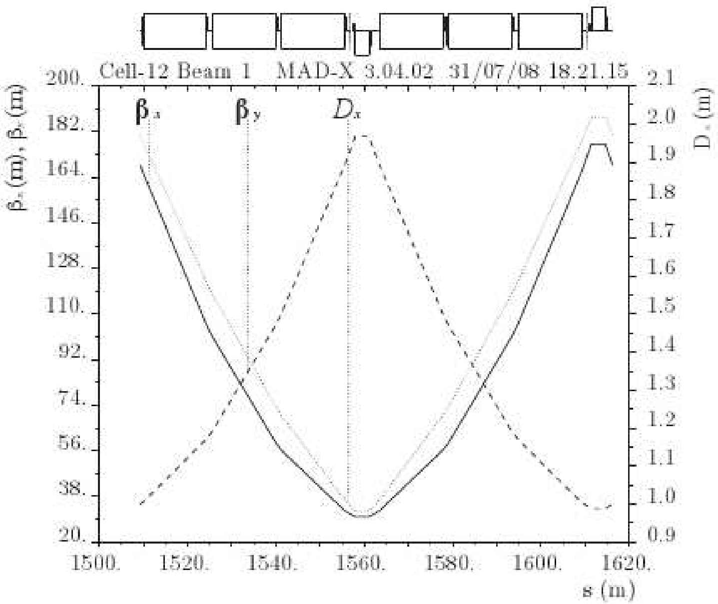


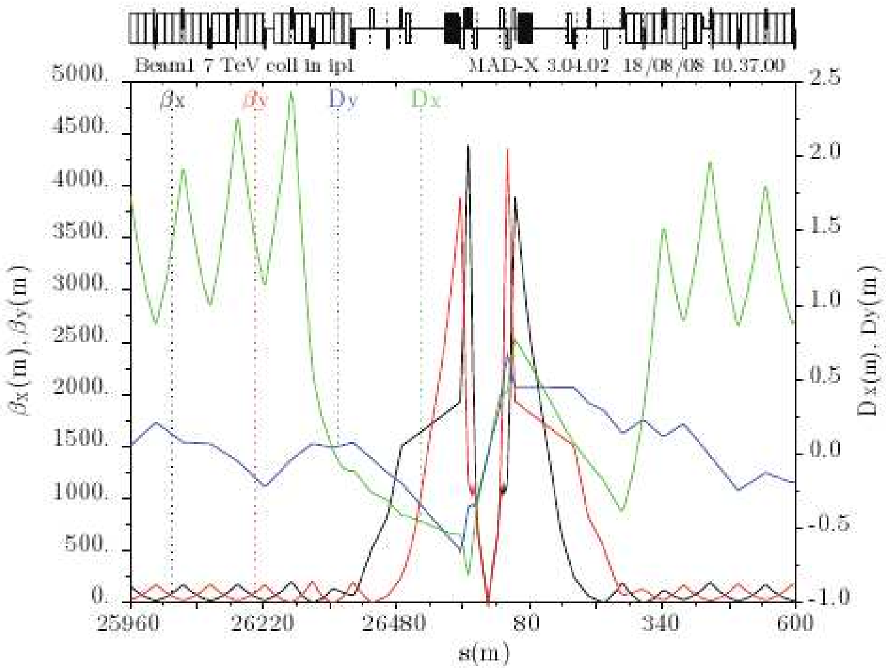
Figure 2.2 Drive beam structure of CLIC

• The highest energy proton collider is LHC. There are plans for luminosity upgrade, requiring modification of IP optics for instance or upgrade of the injector chain, there are plans for high-field LHC based on ∼12 Tesla dipoles.









Normalized emittance $\epsilon/\pi = 3.75\,\mu$m

- The luminosity at LHC writes

$$\mathcal{L} = F \frac{n_b \, N_b^2 \, f_{rev}}{4 \, \pi \sigma^{*2}}$$

Possible upgrade paths :

n_b	2808	number of bunches	increase by bunch spacing 25ns/2 $\rightarrow$ prohibitive heat load
N_b	$1.15 \, 10^{11}$	number of protons per bunch	compromise to heat load : spacing 50ns, $3 \times 1.15 \, 10^{11}$ppb
f_{rev}	11.245 khz		
σ^*	16.7 μm		
θ_c	285 μrad		
σ_z	7.55 cm		
F	0.84	geometrical factor, $\approx 1/\sqrt{1 + (\theta_c \, \sigma_z / 2\sigma^*)^2}$	crab cavities option, F~ 1
L	10^{34} /cm^2 /s		

- There are plans as well for a muon collider, thought to have some advantages over electron collider
    - in particular absence of synchrotron radiation, by contrast with electrons, due to mass $\sim$200 times greater.

- The development of collider accelerators relies on the technological feasibility of
    - higher and higher energies
    - high beam intensities
    - extremely low emittances
    - extremely low β^* values (nano-beams at e+e- colliders, micro-beams at LHC)
    - in rings, ensuring life-times of the order of hours
    - high luminosity

Luminosity

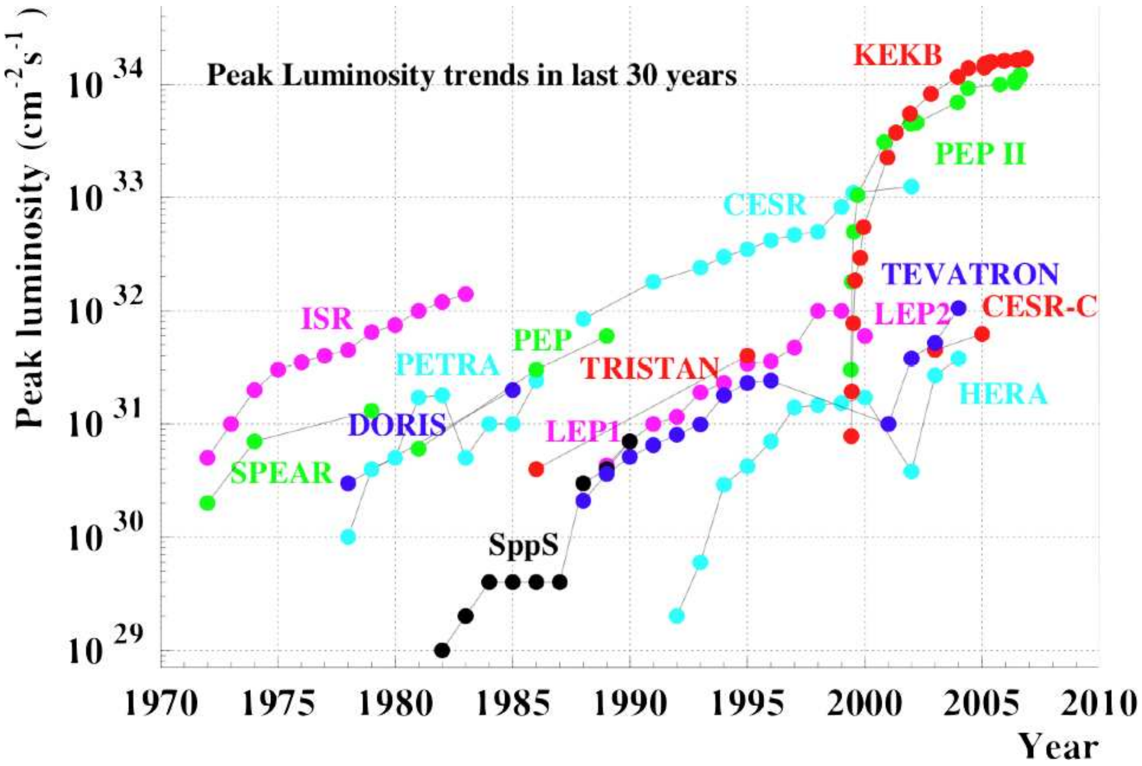
A general expression of the luminosity is

$$\mathcal{L} = nbf_{rev} \int_{overlap} N_1 N_2 ds$$

From designer's viewpoint, $\mathcal{L}$ can take different forms depending on the variables available to design/adjust the machine, for instance,

- it is often written $\mathcal{L} = F\frac{n_b N_b^2 f_{rev}}{4\pi\sigma^{*2}}$ at LHC.

- at super-B, it takes the form $\mathcal{L} = \frac{\gamma_{e\pm}}{2er_e}(1 + \frac{\sigma_y^*}{\sigma_x^*})\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^{e\pm}}\frac{R_L}{R_{\xi_y}}$



Lattice, IP

• The general configurations in colliders include the presence of an interaction region (in linear colliders) or several IR's (in rings), associated with beam transport and acceleration sections, respectively arcs and RF section(s) in rings, extended RF sections in linear accelerators.

• Modern designs of the final focus system (FFS) in electron linear colliders include provision for

- the adaptation of betatron function, corrections as chromaticity and geometric aberrations, using sextupoles, of which higher order geometric or chromatic aberrations may have to be controlled using higher order multipoles, coupling corrections, corrections and tolerances, etc.
- ensuring $\sigma_x >> \sigma_y$ for increased luminosity, $\sigma_z <\sim \beta_y^*$ to minimze the hourglass effect
- large crossing angle to avoid parasitic bunch interactions, in relation various techniques as "crab-crossing" for head-on collisoin, or "crab-waist" collision
- controlling deleterous effects as synchrotron radiation, wakefields, scattering processes, etc.
- beam dump

• Modern designs of IR in e+e- ring collider factories (DAFNE, KEK-B uprgade for instance) tend to adopt the concepts developped in linear collider FFS designs, including the concept of "nano-beams" (extremely small β_y^*), large crossing angle and geometrical compensation of beam-beam effects (crab crossing, crab waist), with the trend to increse luminosity at unchanged beam current (for savings on installed power).

Beam-beam effects

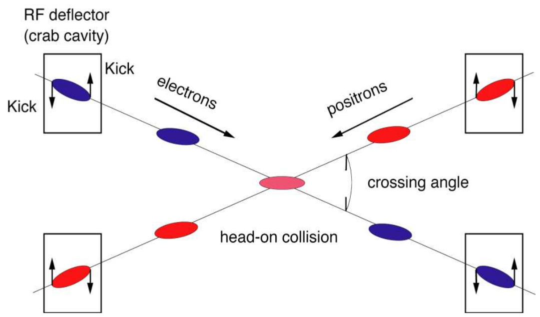
- The lens formed by a bunch from the viewpoint of the opposing bunch is strongly non-linear. The effect is associated with beam size blow-up and lifetime drop.

- The interacton can drive resonances of all orders.

- The linear effect of the lens is cause of tune-shift which is considered as an indicator of the amount of the beam-beam effect.

- The beam-beam tune-shift limit is considered to correspond to the transition from I^2 dependence of the luminosity to I dependence.
  - At SPEAR, $I^2 \longrightarrow I$ set in at a beam-beam tune shift $\Delta Q = 0.03$
  - In the 1980s, the limit was considered to be $\sim$0.05
  - Sp$\overline{\text{p}}$S was operated at total tune-shift (from all intersections) $\Delta Q = 0.02$
  - LEP was operated at total $\Delta Q = 0.03$ (from all intersections), yet reached 0.083 without saturation
  - CESR reached 0.07

• Techniques of beam-beam crossing have been experimented to counteract the beam-beam limit
Numerical simulations indicate that head-on collision greatly improves the luminosity
- KEKB is reaching $\Delta Q \sim$0.1 with crab crossing



• DAΦNE has experimented a “crab waist” method which improves further the luminosity :
the focal plane of the opposing beam is aligned with the incoming beam axis

• Effects to prevent beam-beam tune shift include adjustment of x/y emittances ratio to balance $\Delta Q_{x,y}$, avoiding long range parasitic crossing (e.g., by large collision angle), possible compensation schemes (e.g., at LHC, electrical wire, or electron lens) ...

History

- 1943, again, Wideroe is a pioneer and patents colliding beams (pub. 1953).

He gave serious consideration to the idea of exploring collisions in the center-of-mass system to fully exploit the kinematic advantage of keeping the center of mass at rest to produce larger momentum transfers.

- 1956, the MURA collaboration (FFAG), Wisconsin, propose and experiment (machine shown below) particle stacking to increase beam intensity, opening the way for circular colliders

A first atempt in two-beam storage : acceleration of two 27 MeV opposing e- beams

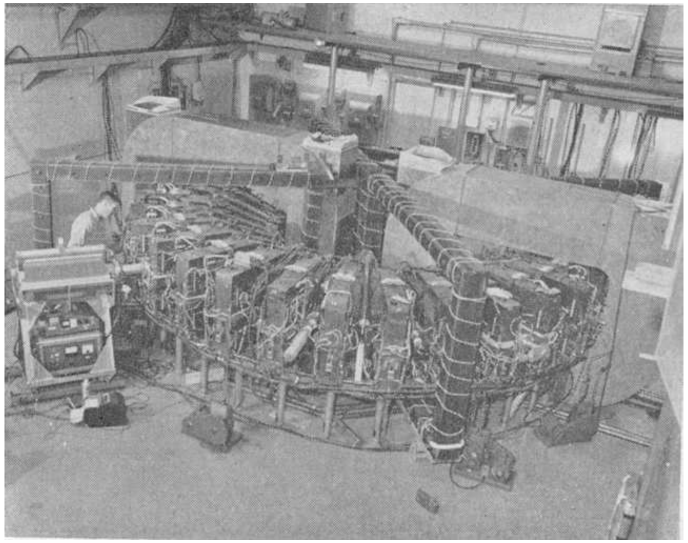
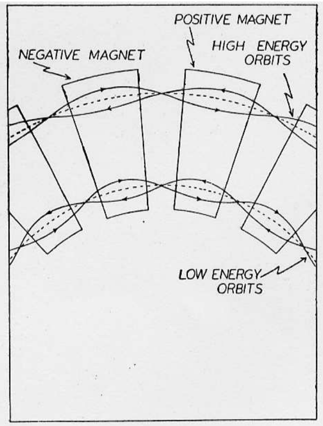
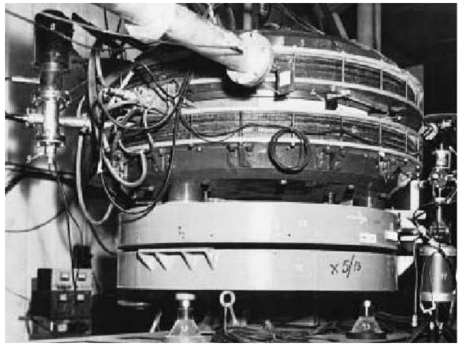


FIG. 1. Schematic diagram of equilibrium orbits in both directions.



MURA developped the method of “momentum stacking” for accumulating intense beams, and succeded storing 20 Amps in that ring.

- 1956, Tigner proposes linear colliders as high-energy electron machines



• 1961, AdA (Anello di Accumulazion), the first e-e collider, a single-ring storage machine (hence $e+$-$e-$), 2×250 MeV, weak focusing, is built in Frascati, Italy.

- Proton accelerators and the strong-focusing method were the stars at nuclear laboratories.
- New types of problems were faced with the AdA experiment : produce the positron beam, vacuum (10^{-9} Torr for beam life-time), injection system, beam-beam collisions, the unpredicted "Touschek effect" (Orsay, 1963. In-bunch e-e scattering causing betatron-to-longitudinal energy transfer and longitudinal loss - Bruno Touschek belonged in the Frascati group).
- In June 1962 AdA is moved to Orsay and its e- linac
- Principal successes : achieved 40 hours storage, intense beams in collision

• AdA is followed by development of higher energy, strong focusing e-e collider, VEPP, CBX, ACO, ADONE ("large AdA", 2×1.5 GeV), etc.

• 1971, CERN operates the ISR, the first hadron collider, an intersecting-ring

Highest intensity ever, 30 Amp stored, based on beam stacking methods developped at MURA, 1950's

• 1971, Blewett proposes the twin-bore superconducting magnet design. Now used in LHC.

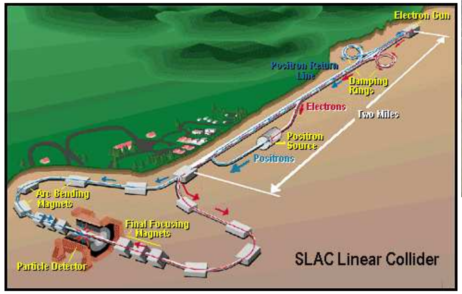
• 1972, physics discoveries at SPEAR trigger strong interest for future collider electron mahines.

• 1972, van der Meer invents stochastic beam cooling, opening the way for hadron, particle-antiparticle colliders.

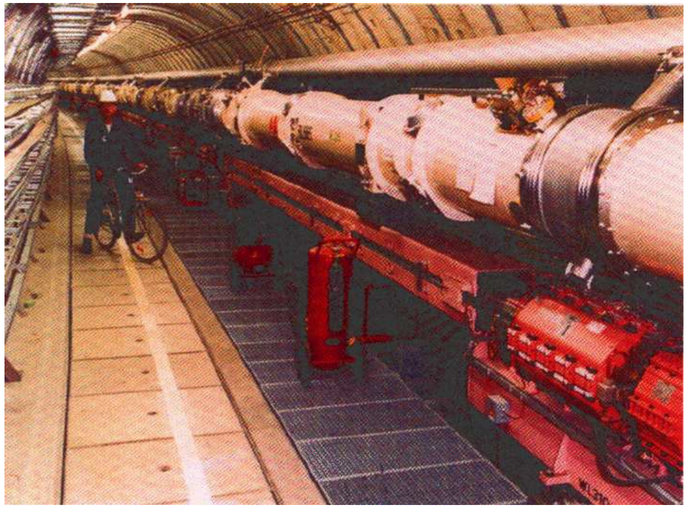
• 1978 The CERN ISR operates the first superconducting magnets (quads) to be used in a synchrotron ring. They are industrially built.

- 1982, CERN converts its SPS to Sp$\bar{p}$S a single-ring proton-antiproton collider.
  (*Note : a world première, first observation on p and $\bar{p}$ undulator light...*)

- 1984, C. Rubbia and S. van der Meer receive the Nobel physics prize for W & Z discoveries at Sp$\bar{p}$S



- 1987, FermiLab (founded 1967), SC Tevatron takes the lead with hadron collider, 2×900 GeV
- 1989, SLC, 2×50 GeV
- 1989, CERN starts LEP, the world highest energy electron-positron collider, 2×45 GeV
- 1991, HERA at DESY is the first facility for colliding protons (920 GeV) against electrons or positrons (30 GeV).
  - Construction May 1984 - Nov. 1990, 10-25 m underground, 6.3 km circumference, 4.7T/4.4K SC magnets (proton ring)



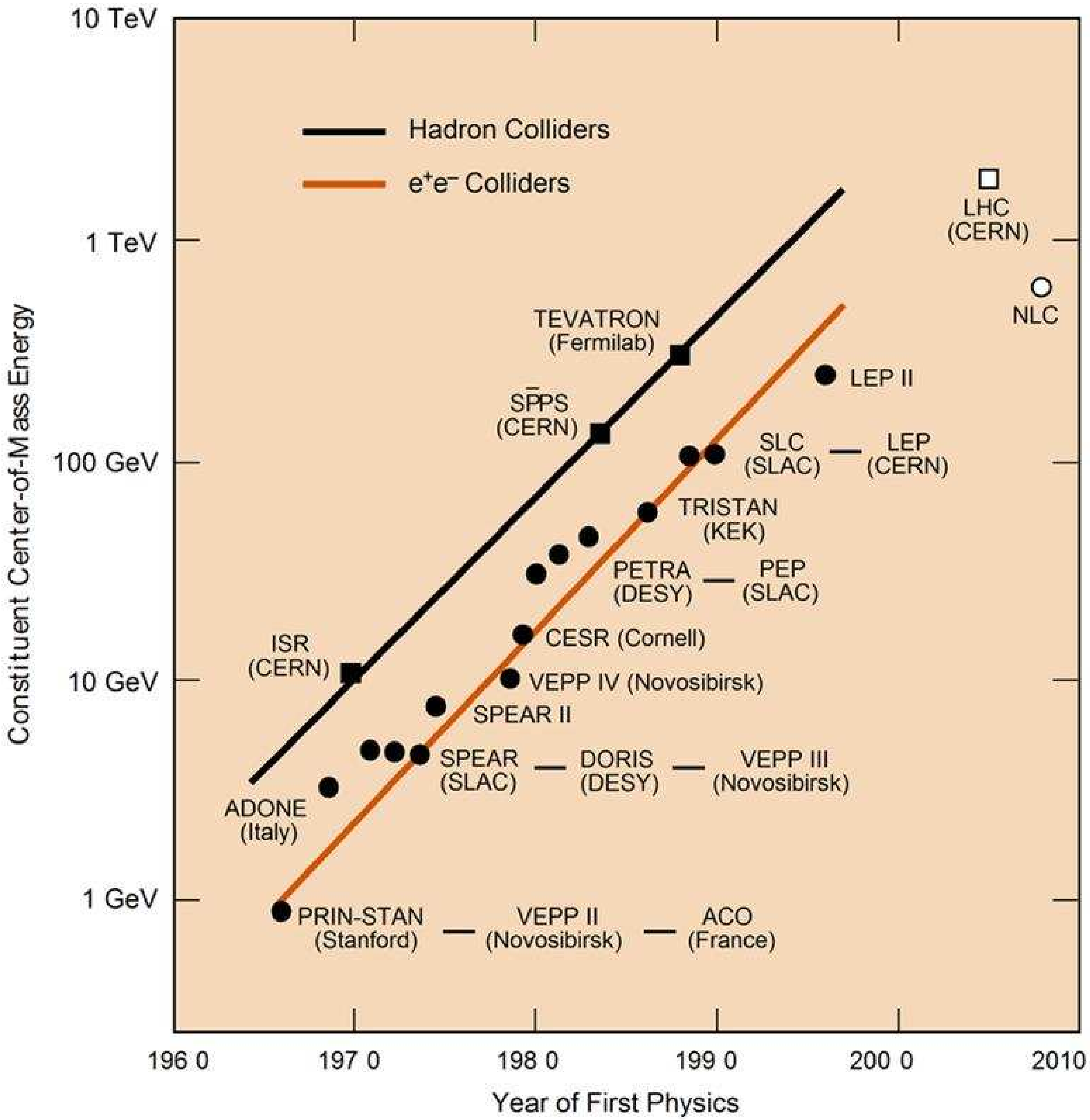
- 1993, the US stops the SSC project... 600M$ are spent for that
- 1995, LEP full with superconducting RF cavities allow reaching 2×100 GeV
- 1999, RHIC at BNL becomes the world facility for colliding ions.
- 2001, FERMILAB, Tevatron “Run 2”, 2×1 TeV
- 2009 ?, CERN plans to start LHC, the worlds highest energy proton-proton collider (superconducting, twin-bore dipoles).
- 20** ?, plans for 0.5 and beyond TeV scale e+e- linear colliders, ILC, CLIC.

Collider rings over the years, an overview

Year	Lepton colliders			hadron colliders			Major discoveries
	CoM Energy	Name/Type$^{(*)}$	$\mathcal{L}$ (/cm^2/s)	CoM Energy	Name/Type	$\mathcal{L}$ (/cm^2/s)	
1962	0.5	AdA / e+e- SR					
1963	0.26	VEPP-I / e+e- DR					
1963	1	CBX / e-e- DR					
1966	1	ACO / e+e- SR					
1969	3	ADONE / e+e- SR					
1971	6	CEA / e+e- SR					
1971				63	ISR / pp DR	$2\,10^{32}$	
1972	5	SPEAR / e+e- SR	10^{32}				ψ, τ, quark jets
1974	1.4	VEPP-2 / e+e- SR					
1974	6	Doris/ e+e- DR	10^{32}				
1976	3.6	DCI / $e^{\pm}+e^{\pm}$ DR					
1978	38	PETRA / e+e- SR	10^{31}				gluon jets
1979	12	CESR / e+e- SR	$8\,10^{32}$				
1979	14	VEPP-4 / e+e- SR					
1980	30	PEP / e+e- SR	$8\,10^{31}$				
1981				630	$Sp\bar{p}S$ / $p\bar{p}$ SR	$3\,10^{30}$	$W^{\pm}$, Z_0
1986	60	TRISTAN / e+e- SR	10^{31}				
1987				1800	Tevatron I / $p\bar{p}$ SR	$2\,10^{31}$	top quark (1995)
1989	3.1	BEPC / e+e- SR	$5\,10^{31}$				
1989	100	SLC/ e+e- LC	$2\,10^{30}$				N_ν
1989	92	LEP I / e+e- SR	$6\,10^{30}$				N_ν, precision SM
1992	160	HERA / $e^{\pm}+p$ DR	$2\,10^{31}$				
1995	200	LEP II / e+e- SR	$2\,10^{31}$				
1997	1	DAFNE/ e+e- SR	$5\,10^{31}$				(Φ factory)
1999	10.6	PEP-II/ e+e- DR	$6\,10^{33}$				(B factory)
1999	10.6	KEK-B / e+e- DR	$2\,10^{34}$				(B factory)
1999				200/u	RHIC-ions / ions DR		
1999				500	RHIC-p / pp DR		
2001				2000	Tevatron II / $p\bar{p}$ SR	$2\,10^{32}$	
2009				14000	LHC / pp DR	10^{34}	Higgs ? SUSY ?

(*) SR : single ring. DR : double ring. LC : linear collider

Collider rings over the years, an overview

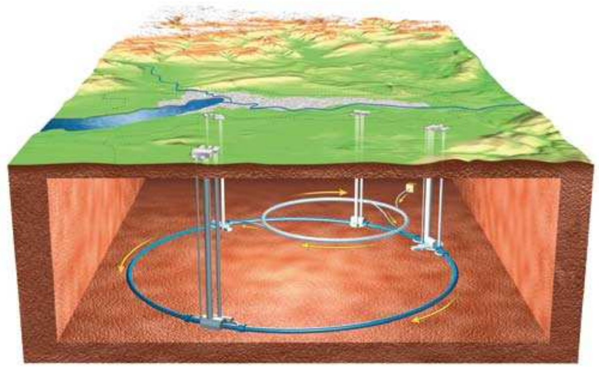


- CLIC

High energy and precision frontiers

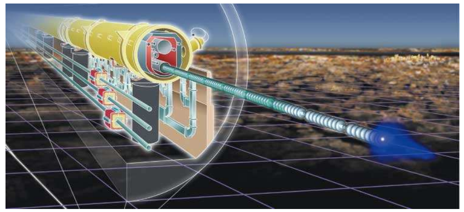
Two domains can be distinguished :

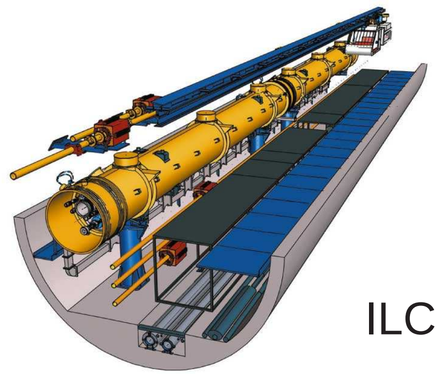
• Energy frontier : create new particles, “find new physics”
pushing the high-energy frontier, i.e. increasing the available centre of mass energy in order to produce and observe new particles



LHC

However this is not the only way to look for NP.

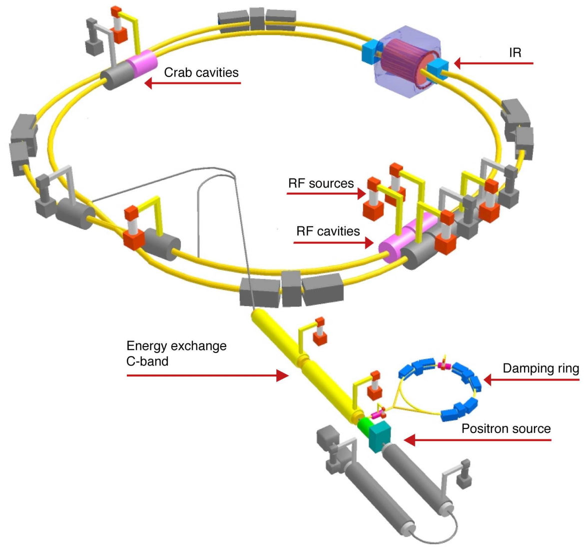




ILC

• Intensity (or precision) frontier : (i) increase statistics on known events (e.g., decay channels), (ii) explore rare events

New particles could reveal themselves through their virtual effects in processes involving SM particles only.
For these indirect of searches the production thresholds are not an issue, the name of the game is rather high precision.
High-precision measurements allow to probe new-physics energy scales inaccessible at present and at next-generation colliders.



super B-factory