UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

INFN Istituto Nazionale di Fisica Nucleare

Not All But a Bit of All About Accelerators

a personal perspective from backstage

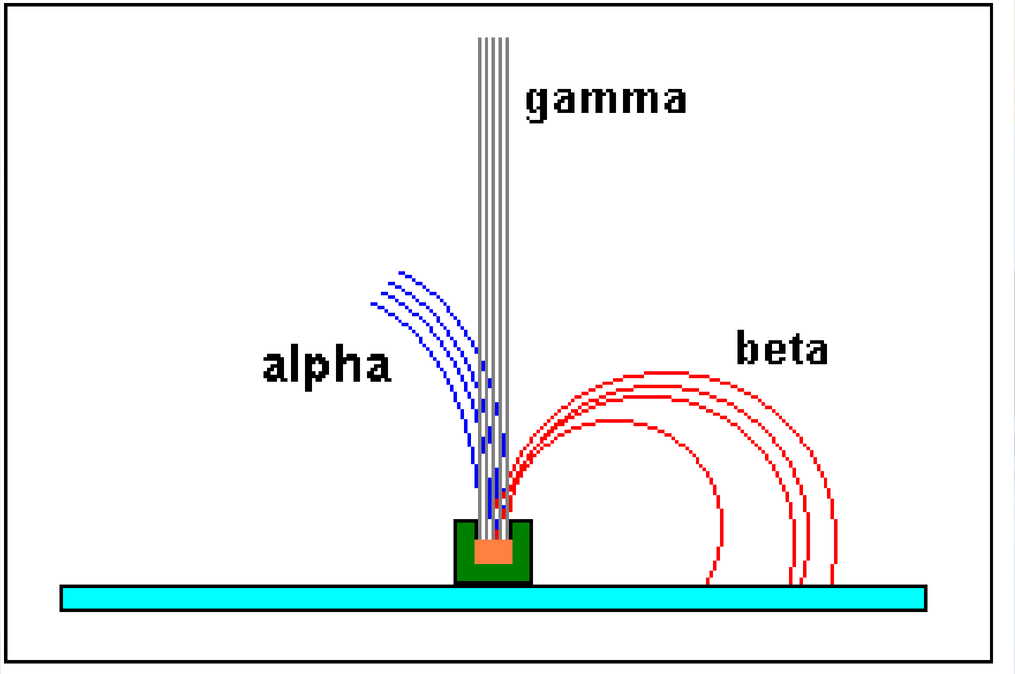
Prof. Vittorio Giorgio VACCARO

AT THAT TIME….(around 1910)

- At that time (about a century ago) radioactivity was most popular among the physics community. From about ten years it was discovered by Becquerel in France. The Curie’s, and then the widowed Mrs. Curie-Sklodowska alone, succeeded with a titanic work to isolate various radioactive elements. Within a very short time the majority of physicists and chemists of the world rushed in research on radioactivity.

AT THAT TIME

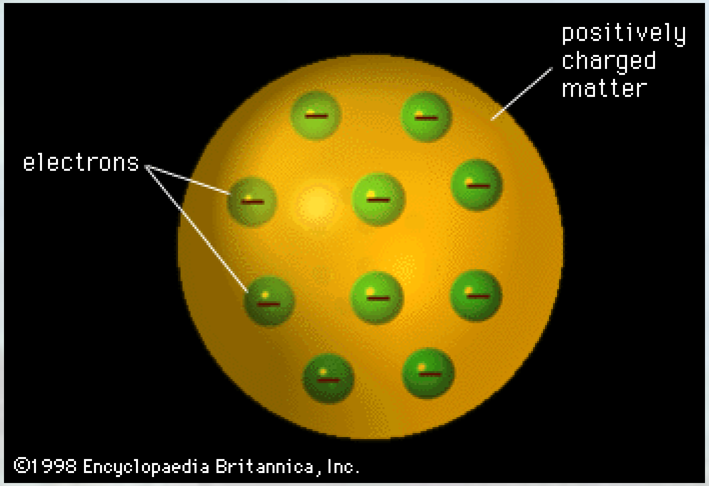
Almost on all High School Physics books, a schematic representation of the experiment which led to the discovery of radioactivity can be found.



The magnetic field is orthogonal to the picture plane

AT THAT TIME

Among the physicists, it was common belief that matter was made of atoms and that these consisted of positive and negative charges, but nothing was known about the arrangement of positive charges within the atom. (Thomson's atom)



The Prehistory: Rutherford

In 1908 Ernest Rutherford was awarded of the Nobel Prize for chemistry. The award citation states: "for his investigations into the disintegration of the elements, and the chemistry of radioactive substances." Among others, he had discovered that the radioactive element thorium released a *radioactive* gas, ***Radon***. Its *activity* consisted in *radiating* energetic alpha particle (ionized Helium atoms of about 4GeV). Rutherford imagined to use them as projectiles for investigating on the atom structure:

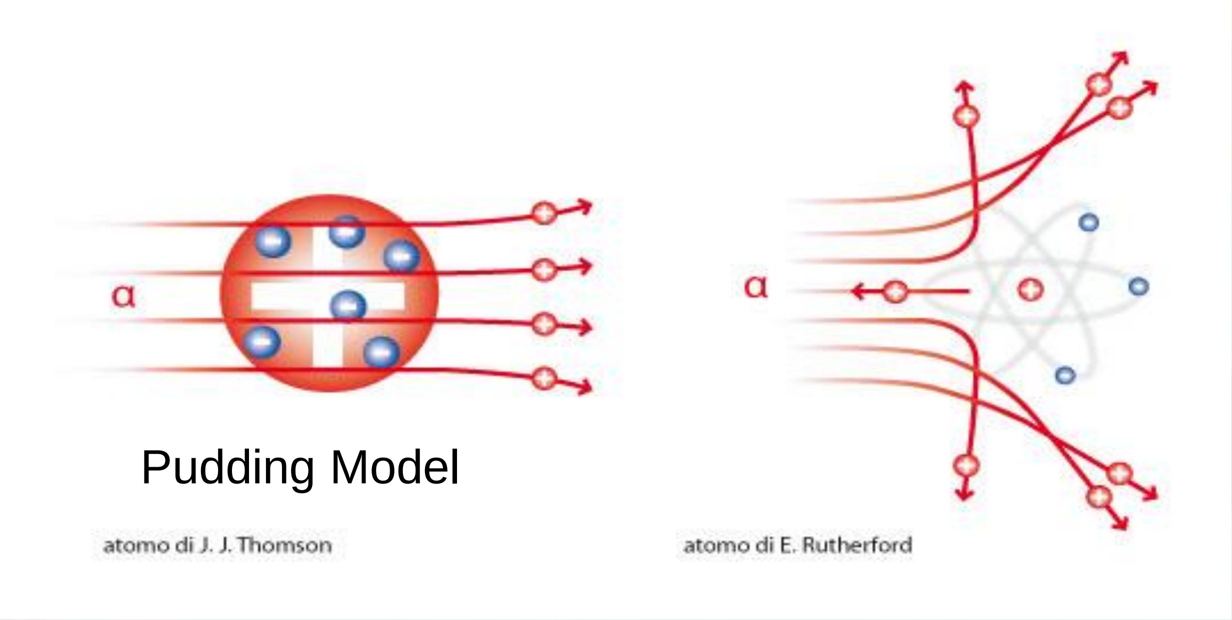
BRUTE FORCE METHOD

THE ACCELERATOR ERA WAS BORN

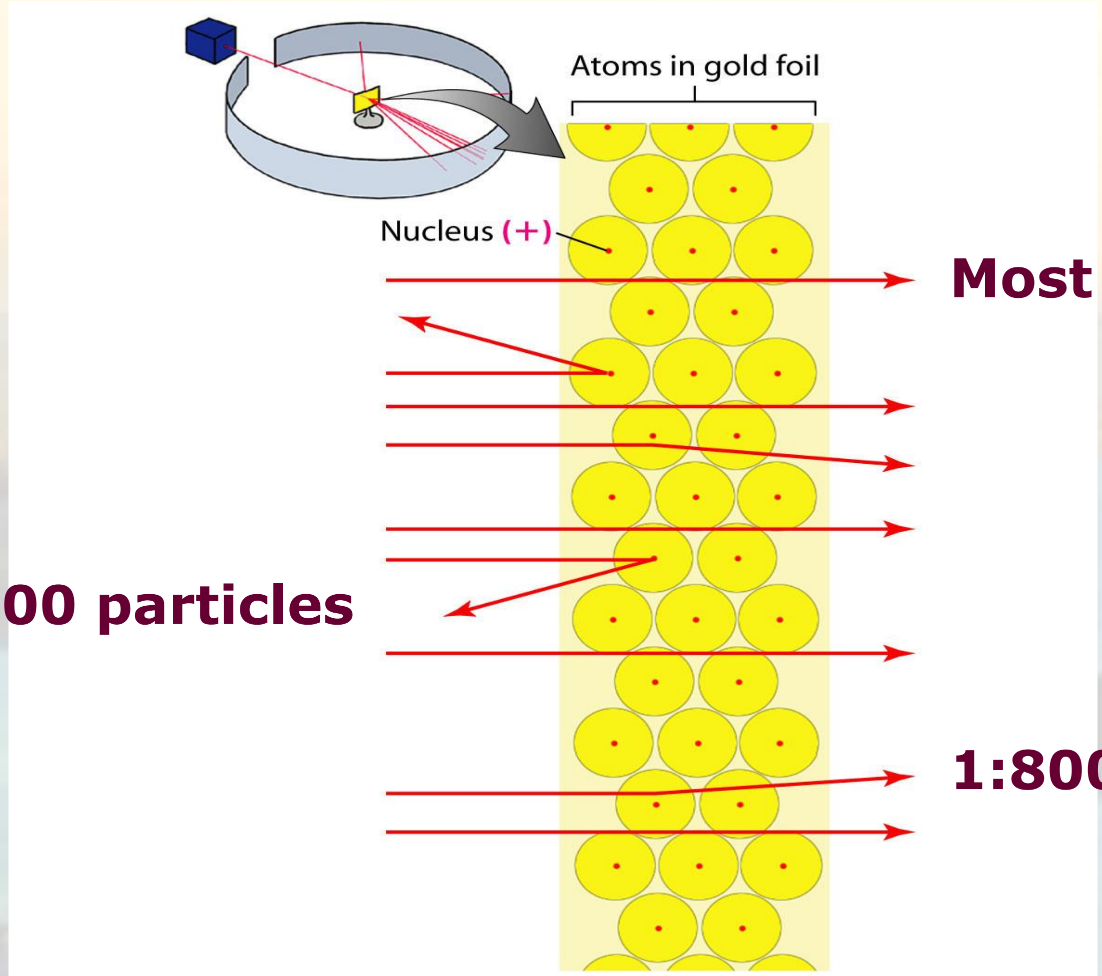
Two models in comparison

This classic diffraction experiment was conducted in 1911 by Hans Geiger and Ernest Marsden at the suggestion of Ernest Rutherford

[Rutherford was] a "tribal chief", as a student said.



The crucial experiment

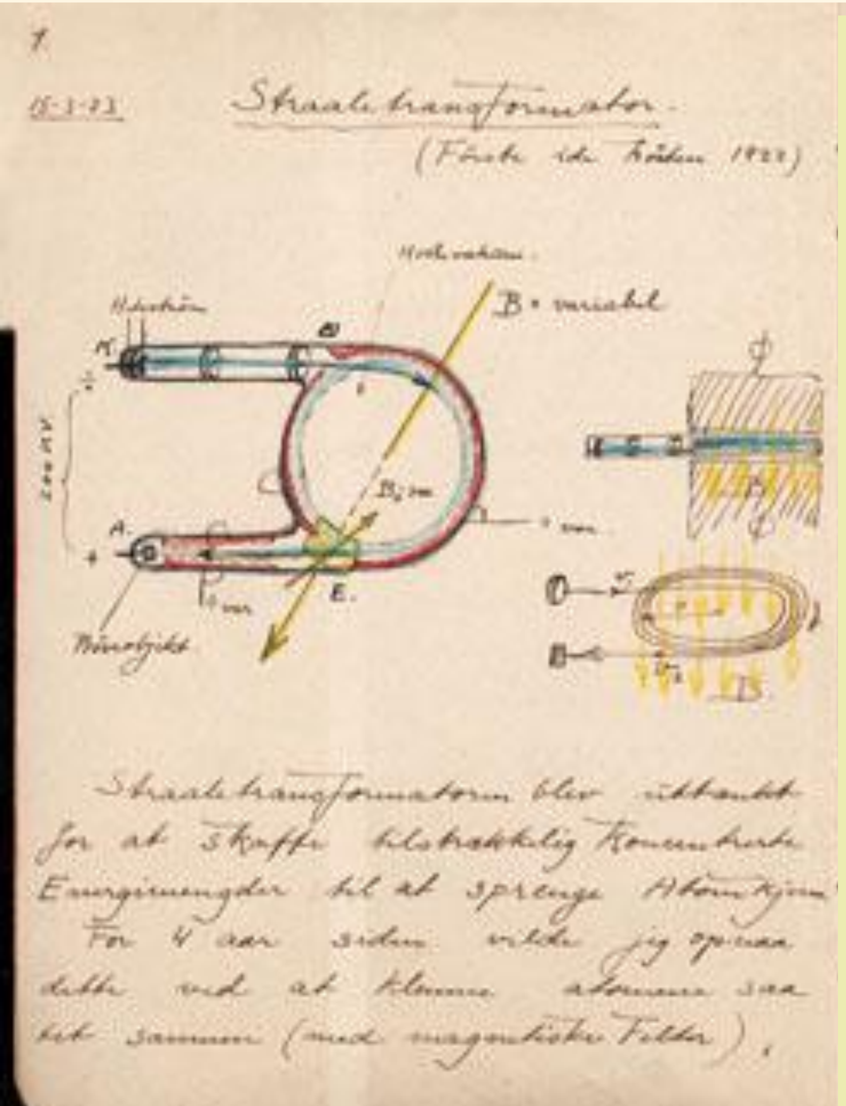


Convincement to produce artificial energetic projectiles.

Rolf Wideroe

- during his studies at the University of Aachen, Rolf Wideroe , barely 20 years old, had already dreamed of making a "radiation transformer ", later called betatron, which was much later very useful in the production of X-rays in hospitals.

Rolf Wideroe



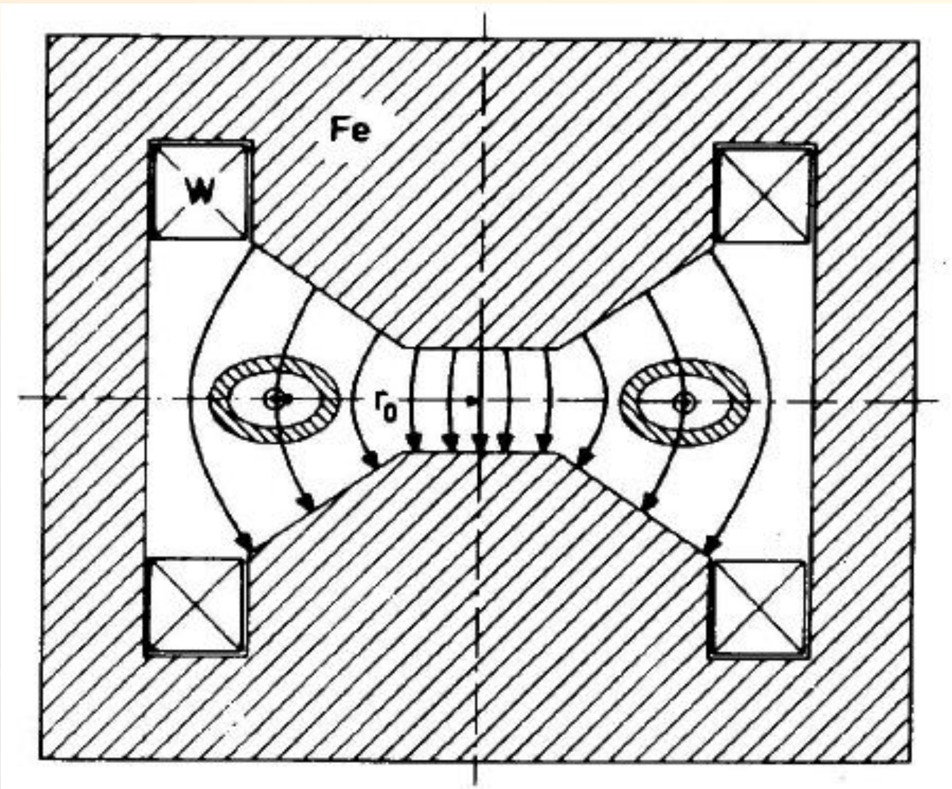
The genius of this idea lies in the fact that the magnetic field bends the charged particles trajectory keeping them on a circular orbit (Lorentz force) and, when it intensifies, the particle energy increases (Faraday law).

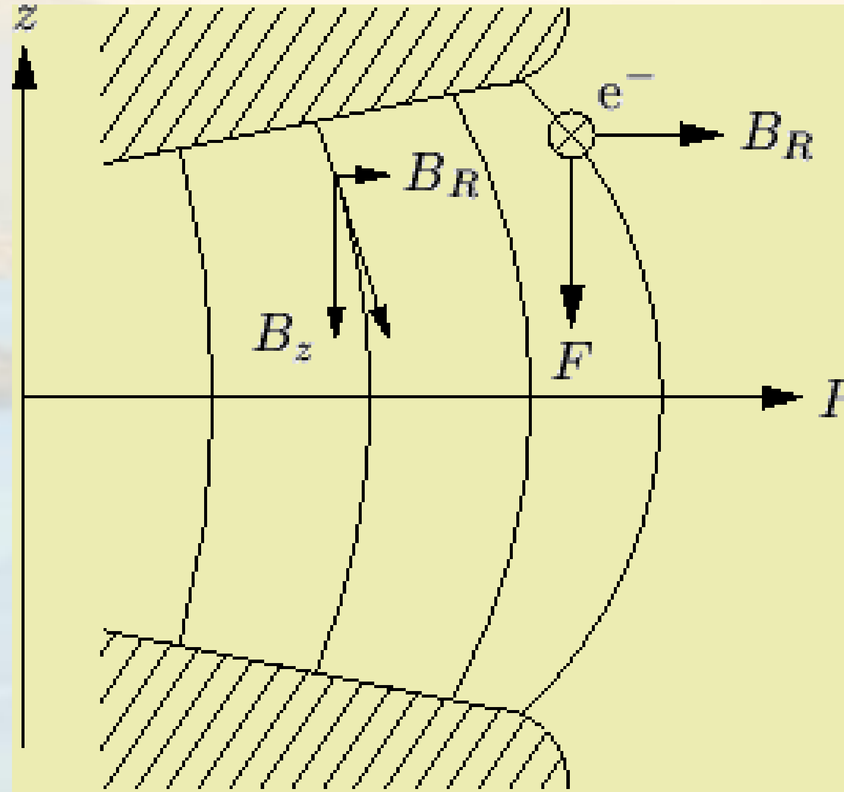
He presented this project as a PhD thesis in engineering at the University of Aachen.

Rolf Wideroe Formula

$$B_{orbit} = \frac{1}{2} B_{gap}$$

Weak Focusing $\frac{\partial B_z}{\partial R} = \frac{\partial B_R}{\partial z}$





To find a good compromise between the vertical and horizontal focusing

The Betatron

- The transformer was built, but the experiment failed for insufficient vertical focusing

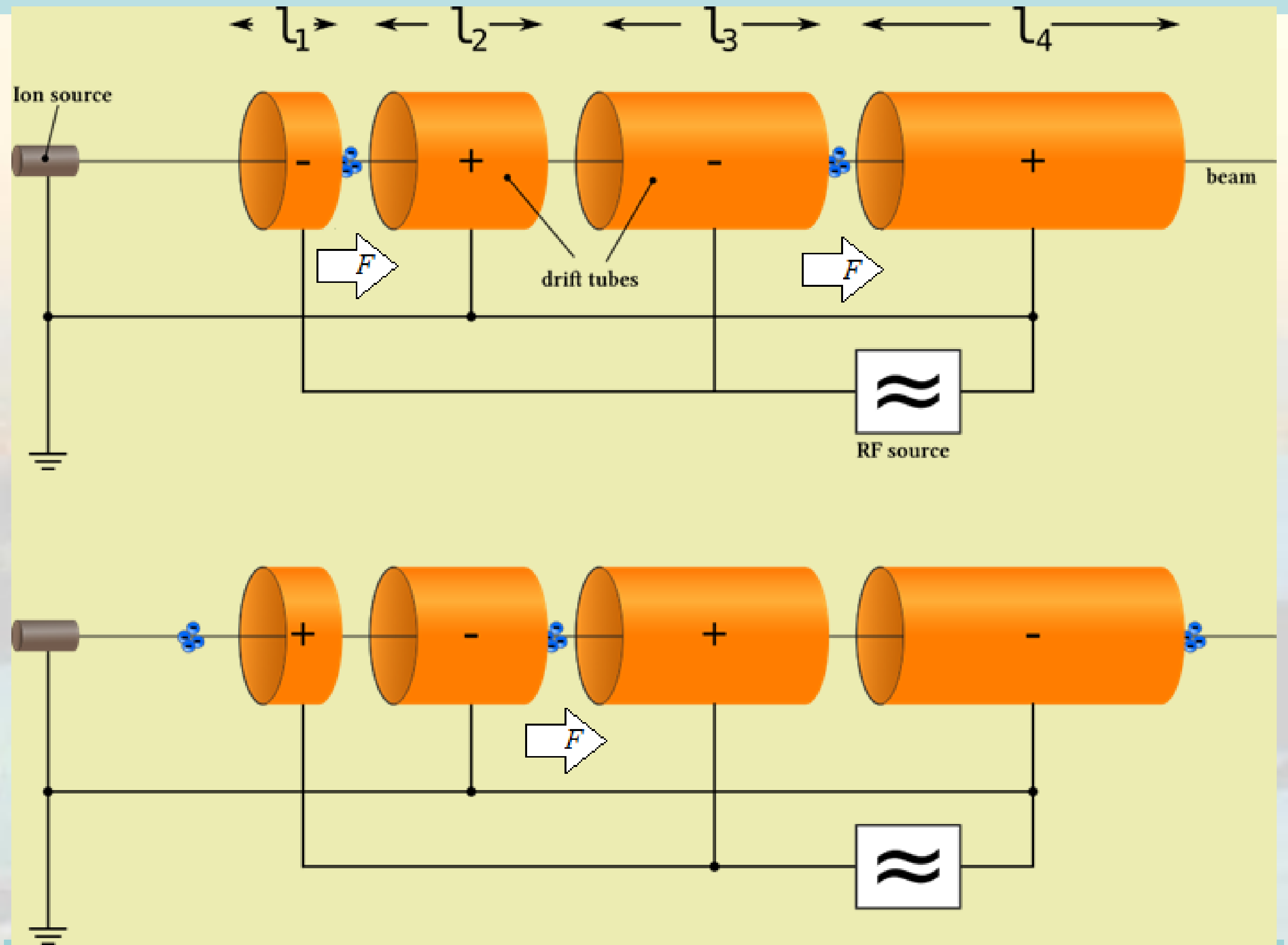
The Betatron, reinvented by Donald Kerst in 1940 in USA, was then employed in particle physics experiments to provide high energy electron beams up to about 300 MeV. If the electron beam is directed on a metal plate, the betatron can be used as a source of energetic X-rays or gamma rays; X-rays may be used in industrial and medical applications (mainly in radiation oncology)

Ausser-ordentlich-hoch-geschwindigkeit-elektronen-entwickelnden-schwer-arbeits-bei-gollitron,

Donald William Kerst

Vintage atmosphere: Kerst is wearning a double-breasted suit.

Wideroe 2nd attempt



Sketch of the Ising-Widerøe linear accelerator concept, employing oscillating fields (1928)

Rolf Wideroe and Bruno Touschek

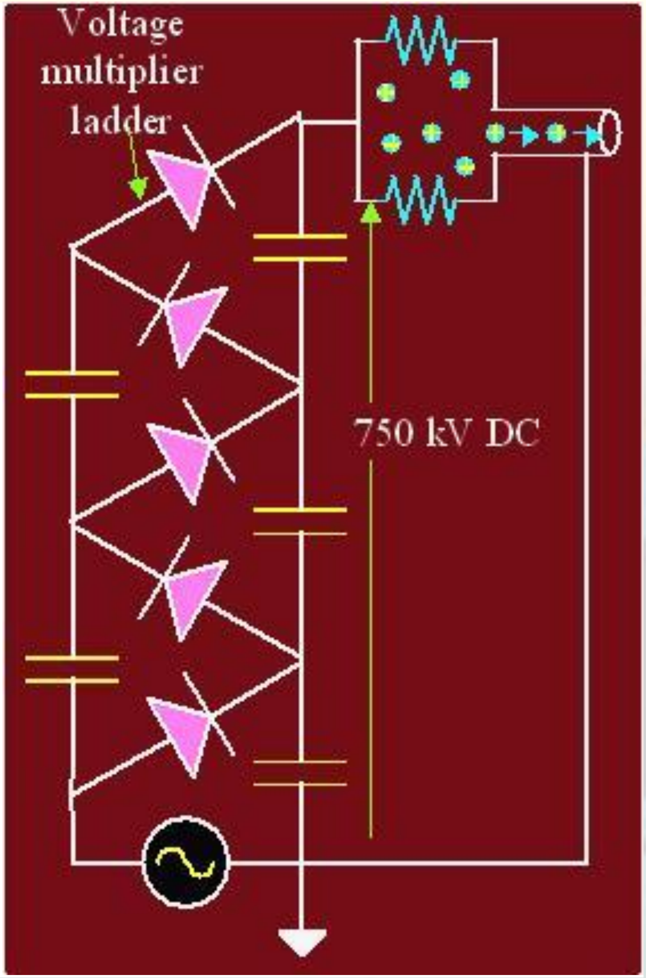
- Rolf Wideroe was a volcanic mind: in scientific circles he is credited of inventing the betatron, synchrotron, linear accelerator, the storage rings for colliding beams. The latter invention pioneered about 40 years the realization that as we will see later was carried out in Italy at the laboratories of Frascati
- Hamburg1943. Wideroe meets Bruno Touschek. The imprisonment of Touschek by the Nazis.
- The "totenstraal" (death ray).The imprisonment of Wideroe by Allied Forces

Meanwhile… Cockcroft & Walton

- The thrust impressed by Rutherford bore fruit that matured after the break of the First World War: accelerators based on potential drop.

- In the late 20's, Cockcroft & Walton, two researchers belonging to Rutherford Team, made use of a new device that technology recently offered them: the diode. They built the apparatus shown in the following page. Despite the complexity, seeming only, the apparatus is simple

Cockcroft & Walton ..



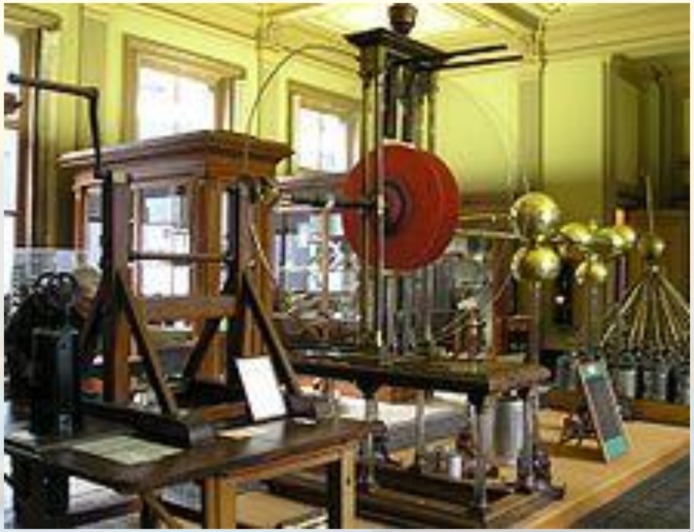
Cockcroft & Walton

- Cockcroft and Walton in 1932 used this circuit design to power their particle accelerator, performing the first artificial nuclear disintegration in history. On ‘52 they got the Nobel Prize.
- It is interesting to remark that soon it found a technological use, for instance, for testing devices to be exposed to high electric fields; use that is still practiced.
- During the 30’s Cockcroft- Walton accelerator has quikly had its time

- **REMARK**: The circuit was invented much earlier, in 1919, by Heinrich Greinacher, a Swiss physicist.

Back to Thales: Van Der Graaf Accelerator

Ancient cultures around the Mediterranean knew that certain objects, such as rods of amber, could be rubbed with cat's fur to attract light objects like feathers. Thales of Miletus made a series of observations on static electricity around 600 BC.

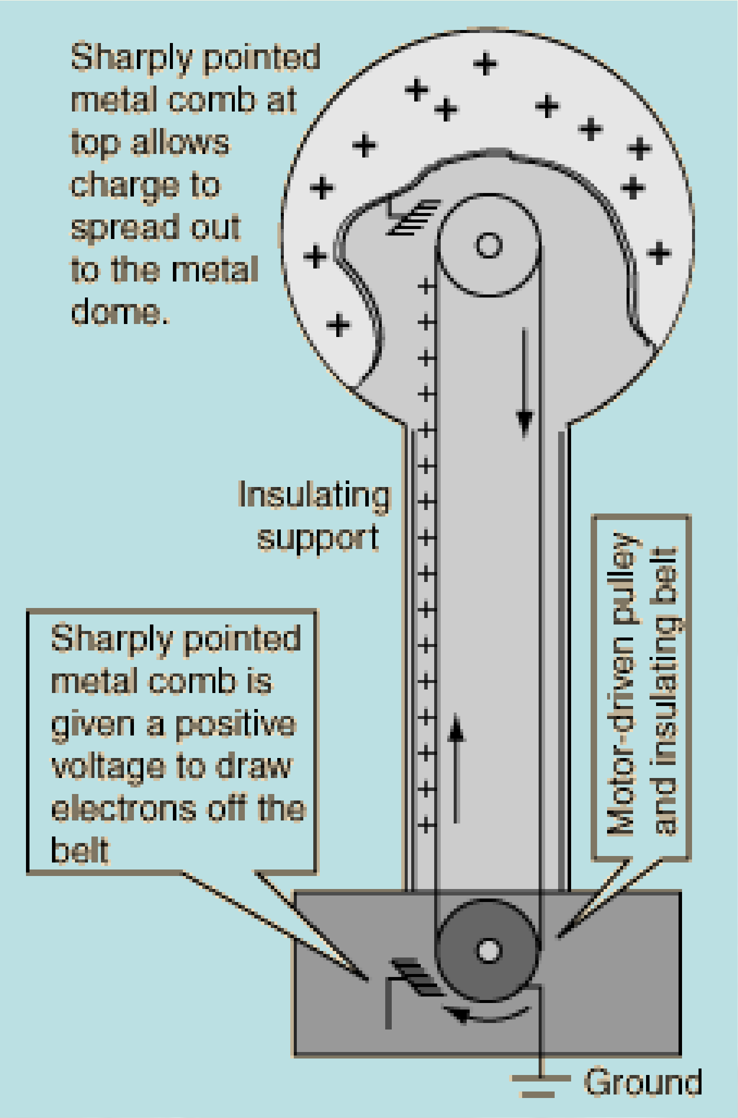


Martinus van Marum's (1784) Electrostatic generator at Teylers Museum (Nederland)

In the eighteen century a number of devices were conceived and carried out which were able to produce very large difference of potential resorting to the same effect described by Thales.

Last century, at the end of 20's **Van Der Graaf** at Princeton University built an electrostatic generator based on the phenomenon described by Thales, which got its name from the inventor. As an accelerator it was more long-lived than Cockcroft-Walton.

Van der Graaf Generator



This system is simple and at the same time ingenious: the positive charge is "sprayed" at low potential (10kV) on the belt which drags it inside the sphere; here is neutralized by negative charges "sprayed" As the belt continues to move, a constant 'charging current' travels via the belt, and the sphere continues to accumulate positive charge until the rate that charge is being lost (through leakage and corona discharges) equals the charging current. The larger the sphere and the farther it is from ground, the higher will be its peak potential. A student of high school can try to build an accelerator. The cost was $90

Van de Graaff generator at The Magic House, St. Louis Children's Museum

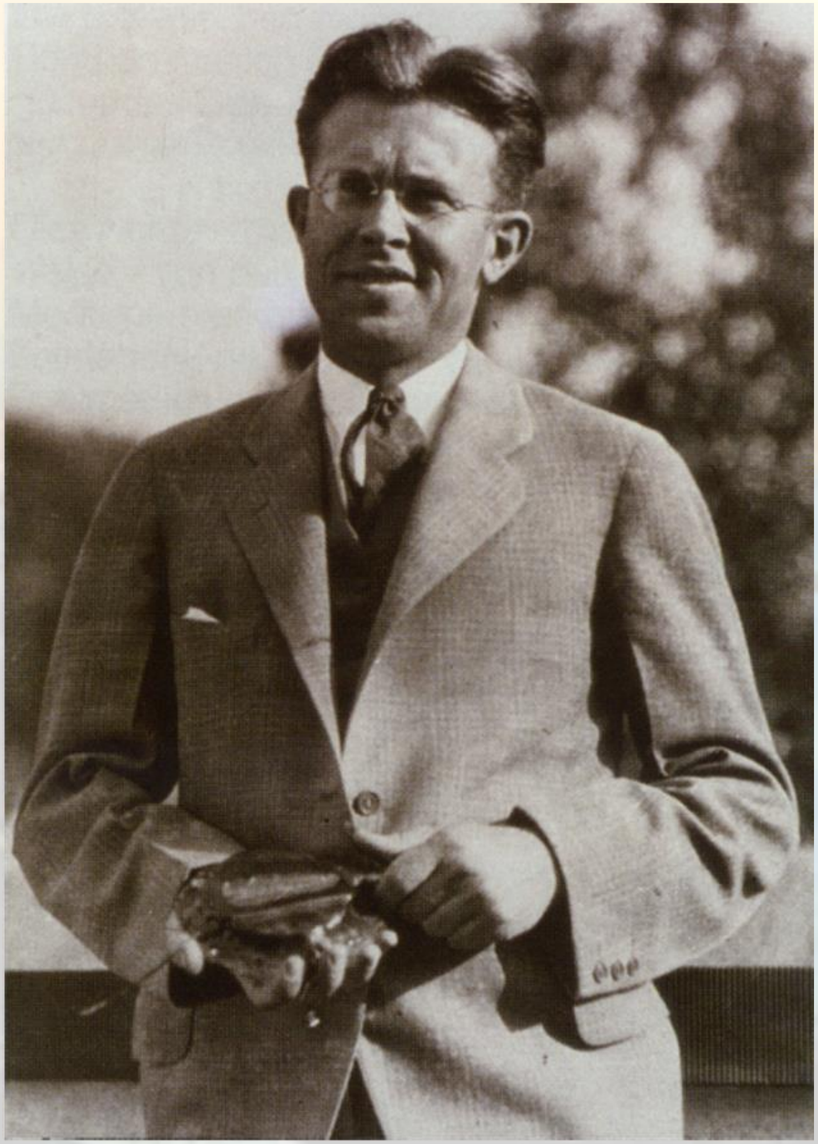
Today it is still used as an accelerator to generate energetic particle and X-ray beams in fields such as nuclear medicine..

A Van Der Graaf generator for class room demonstrations

Van Der Graaf Accelerator

- Many microamps of electrons can be accelerated by Van Der Graaf. Currently Van Der Graaf are commercial machines with potential ranging from one million to 25 MV (Mega Volt = million volts). By way of comparison, the short pulses used in research on lightning reach 10 MV and the potential in the clouds just before the lightning discharge is about 200 MV. The Van Der Graaf are often used in the analysis and modification of materials, especially in environmental research
- The need to investigate more and more profound aspects of matter behavior imposed to seek accelerators with increasing current intensity and larger and larger energy.

Ernest Orlando Lawrence: Mr Cyclotron



In Berkeley **Ernest Orlando Lawrence** had raised the issue of meeting physicist needs of simple and relatively inexpensive research engine. He was a man of harsh frugality. He was used to not hesitate to fire his co-workers, as he did twice with R. Wilson, who later become director of Fermilab. He got the Nobel price for the invention of the cyclotron.

WIDEROE tells about us E. O. Lawrence

- At this point let us give the floor to Wideroe that, much later, met Lawrence who told him about how he conceived the cyclotron: "Lawrence, once told me that while attending a conference in Berkeley, bored by presentations, went to the library and found my thesis in the journal "Archiv für Elektrotechnik". He watched just the drawings and formulas because he understood little or nothing of German. From the illustrations, he immediately understood the principle of my drift tube. Luckily, his ignorance about German did not let him to understand my misgivings, reported in the paper, about the stability of the orbits in circular accelerators. "

Lawrence catchall…

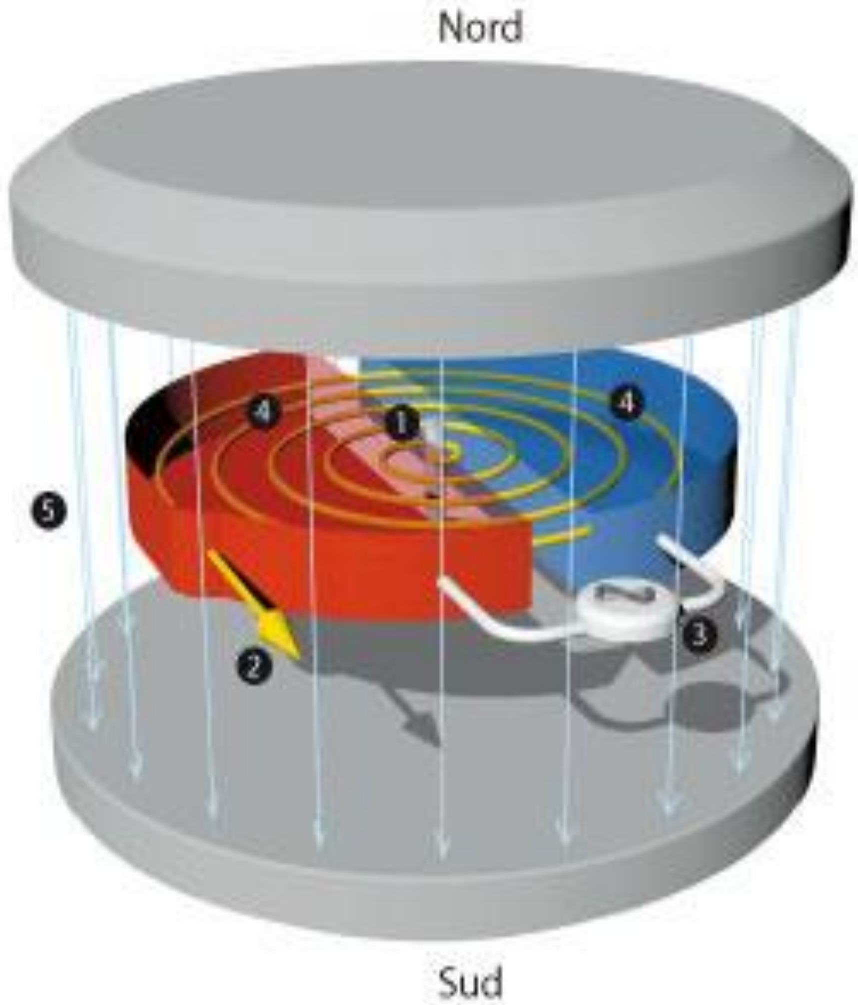
- Rolf Wideroe continues: “Back to (Lawrence) Radiation Laboratory, together with his co-worker David Sloan, built his first linear accelerator for mercury ions, which reached the energy of 1,26 MeV. It was an amazing success!” From then on and until recently, the paternity of linac was attributed by some literature to Lawrence.

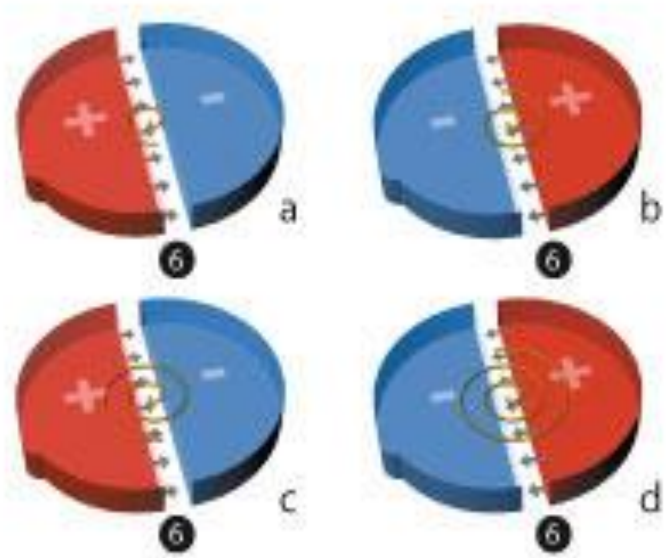
- Lawrence had chosen to play it safe, but meanwhile he was thinking of a structure that would return the beam back on his track in order to save on the number of RF power supplies

Lawrence catchall…

- Resorting to linear accelerators concept would mean to add more drift tubes and then further expensive power supplies.
- Only afterwards, with the development of powerful microwave generators such those used for Second War radars, the idea of linear accelerators for both for electrons to protons was revived and extensively developed. This solution is still very up to date, and has witnessed impressive achievements: the Stanford Linear Accelerator, 3 km long, in 1966 accelerated electrons to 20 GeV and electrons and positrons to 50 GeV in 1989.
- Physicists started requiring particles energy comparable to those of unstable nuclei used by Rutherford, but with much higher intensity of highly collimated beams. Lawrence's goals were very ambitious: to generate intense beams of tens of MeV of "heavy bulletts".

The Cyclotron





1. Positive ions source
2. Positive ions beam
3. RF power generator
4. D shaped electrodes (Dee's)
5. Magnetic Field
6. Electric Field

The Cyclotron

- Lawrence resorted to Wideroe scheme. But with constant magnetic field. As accelerating electrodes, he devised a structure formed by the two halves of a very flattened conductive cylinder (pillbox): one half was connected to ground and the other to an RF generator.
- The charged particles, accelerated after each crossing through the gap between the electrodes, travel along the half circumferences of increasing radius. Nevertheless their angular velocity stay constant. He discarded the use of electrons.

Lawrence had noticed that ions of rest mass m_o and charge e moving in a uniform magnetic field B circulate at a constant frequency independent of energy:

$$\omega = \frac{eB}{m_o c}$$

From then on named cyclotron frequency

The Cyclotron

- The cyclotron, built by Lawrence in collaboration with his student Milton Stanley Livingston, a Lawrence collaborator accelerated protons at expected, though modest, energy of 80 keV. It was 1932 and the operating principle was then demonstrated. Livingston declared: " When the cyclotron was built , Lawrence received the Nobel prize and I got the title of Doctor of Philosophy ... ".

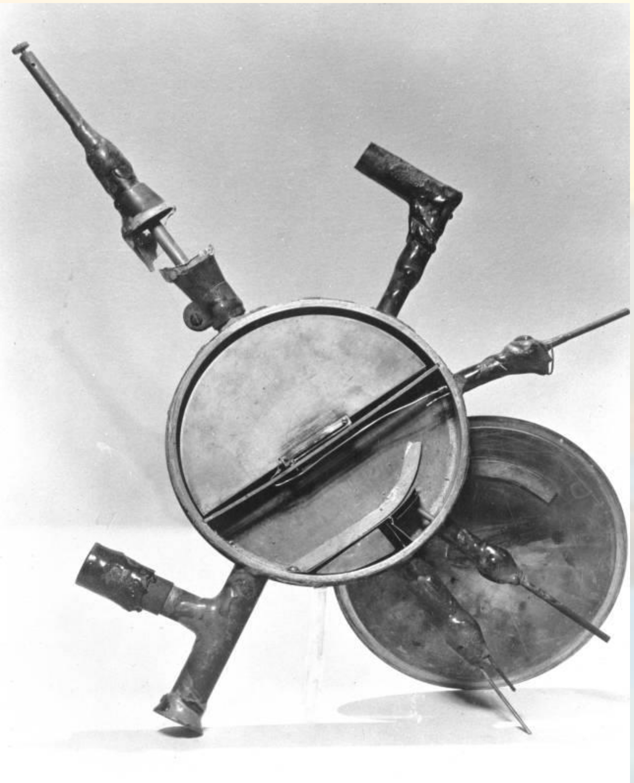
From the back stage: after some unsuccessful tests, Livingstone insisted to apply some changes that, according to his thought, could solve the issue. Lawrence disagreed and did not give his consent. Profiting of Lawrence temporary leave, Livingstone applied the changes and they resulted in a successful test.

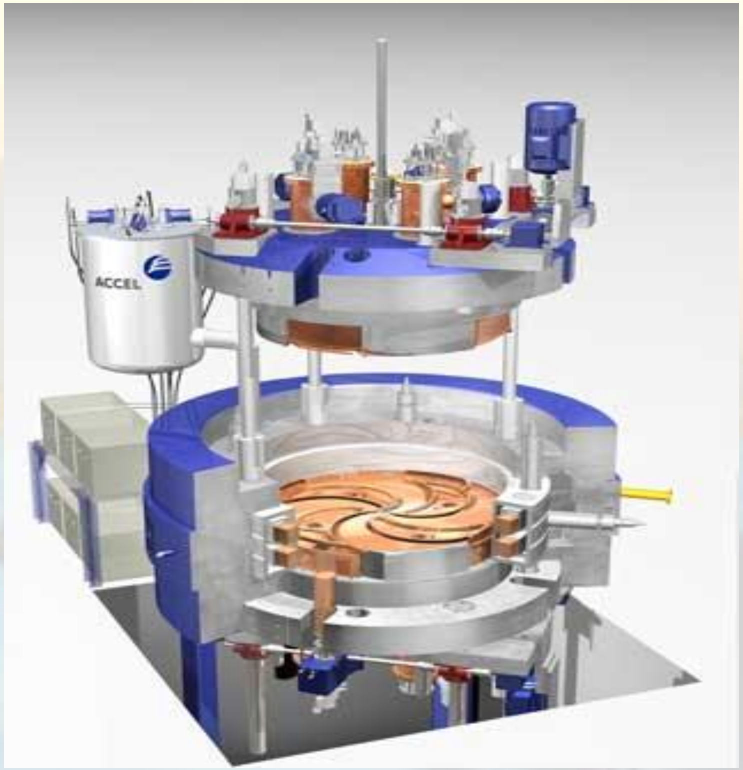
Cyclotron’s limits

$$\omega = \frac{eB}{\gamma m_0 c}$$

- The researchers began building cyclotrons increasingly large and increasingly higher performance. However, for relativistic energies, some limitations appeared. The cyclotron frequency decreases with the increment of the relativistic mass; this effect causes the loss of synchronism between the bunch gap crossing and the phase of the RF power:
- By means of spiral shaping of the Dees one can introduce a compensating correction to the RF phase delay. However, that remedy can work only to some extent (in terms of energy).
- decreasing the frequency of the generator (Synchrocyclotron). However, apart for energy limitation, this solution can accelerate only one bunch and the next one can be accelerated only when the last has been ejected.

Cyclotron's limits





The cyclotron continues to be used for its versatility, simplicity and robustness. It is not a Ferrari but an overpowering bulldozer! It has a very wide range application in fields such as cancer treatment and the production of radionuclides employed in diagnostic imaging.

The Guinnes Record Cyclotron at Gatchina, Russia

Its weigth exceeds of 25% the weigth of Eiffel Tower (10,100 tons)!

What we have learned

Exploring the infinitely small requires more and more energetic projectiles. This may be done only with charged particles beams with quite demanding features: strong collimation; high intensity; high energy.

1. Horizontal focusing competes with the vertical one: weak focusing
2. DC accelerators suffer limitation in energy and current.
3. Cyclotrons are limited in energy
4. Synchronization and focusing are important issues to overcome.

The new generation: the Synchrotron

In order to meet the new requirements a new generation of circular accelerators, the synchrotrons, was born. They are based on the idea that the apparatus should spatially separate guiding devices (magnets of various types) from the one that accelerates (resonant cavities capable of generating high fields with variable frequency, ***f***). The latter apparatus must be capable to be synchronous with particle crossing (remember Wideroe linac in slide 13), which implies that ***f*** must be a multiple integer of the particle revolution frequency***.*** The beams of charged particles traveling circular closed trajectories are bent and collimated by the strength of the magnetic fields.

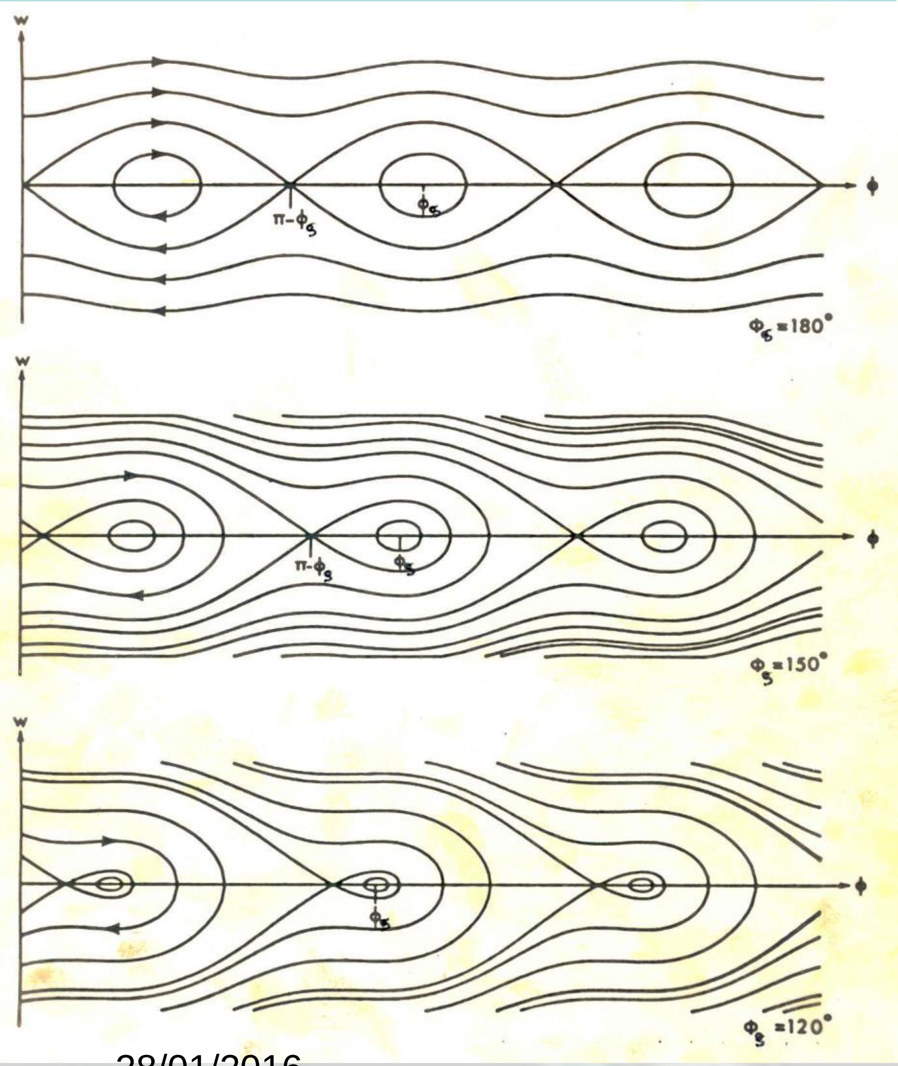
The 1st synchrotron: the Cosmotron

http://www.lns.cornell.edu/~dugan/USPAS/

- The basic principles of synchrotron design (phase stability) were proposed independently by Vladimir Veksler in the Soviet Union (1944) and Edwin McMillan in the United States (1945). According to this principle, it is possible to accelerate bunches of charged particles of finite dimensions. Those dimensions are as smaller as higher is the acceleration.

http://www.lns.cornell.edu/~dugan/USPAS/

The phase stability principle



The areas of stable motion (closed trajectories) are called “BUCKET”. The phase extension of the bucket is maximum for ϕ_s =180º (or 0°) which correspond to no acceleration. As the synchronous phase gets closer to 90º the buckets gets smaller.

Nothing can be obtained without paying something.

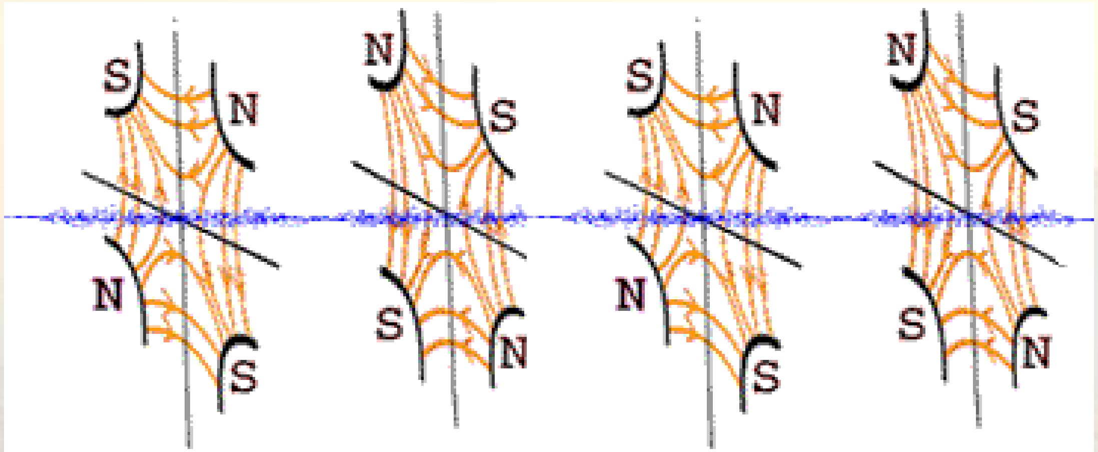
A Glance to the Future:
The great Leap Forward

Since when Brookhaven's Cosmotron went into operation in the early 1950's, scientists knew that achieving the higher energies needed for future research was going to be a difficult problem. Calculations showed that, using existing technology, building a proton accelerator 10 times more powerful than the 3.3GeV Cosmotron would require 100 times as much steel. Such a machine would weigh an astronomical 200.000 tons.

The great Leap Forward: The strong Focusing

While the first synchrotrons and storage rings strictly used the toroid shape, the strong focusing principle independently discovered by Ernest Courant and Nicholas Christofilos allowed the complete separation of the accelerator into components with specialized functions along the particle path, shaping the path into a round-cornered polygon. Some important components are given by radio frequency cavities for direct acceleration, dipole magnets (bending magnets) for deflection of particles (to close the path), and quadrupole / sextupole magnets for beam focusing.

The Great Leap Forward:
The Strong Focusing

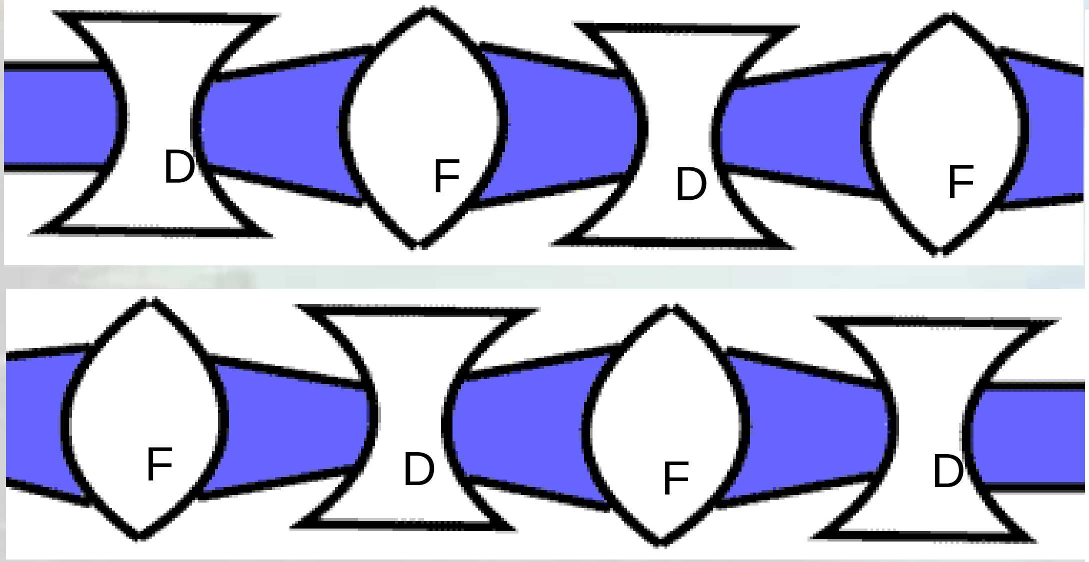


$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{\Delta}{f_1 f_2}$$

$$if \quad f_1 = -f_2$$

$$and \quad \Delta = |f_1|$$

$$\frac{1}{f} = \frac{1}{|f_1|}$$



Alternating the focusing and defocusing actions, one gets focusing in both planes.

The cost to be payed is to take care of betatron instabilities!

AGS

Alternating Gradient Synchrotron

33 GeV on July 29, 1960

The Already ‘Passed by’ Future

Even before the successful achievements of AGS, the scientific community was aware of another step needed to revolution the accelerator techniques. Indeed, the impact of particles against fixed targets is very inefficient from the point ofview of the energy actually available for new expeiments: much more efficient could be the head on collisions between high-energy particles.

BUT THERE IS A REAL NEED OF COLLIDERS?

- With increasing energy, the energy available in the Inertial Frame (IF.) with fixed targets is incomparably smaller than in the head-on collision, as Wideroe thought some decades before. If we want the same energy in IF, using fixed targets one should build gigantic accelerators. In the fixed target case, according to relativistic dynamics, an LHC-equivalent beam should have the following energy:

$$E_{FT} = 2\gamma_{LHC} E_{LHC} \cong 15 \times 10^{3} E_{LHC}$$

- In order to compensate the decrease of the collision probability: design **highly collimated beams with high current intensity**.

The Contest: Frascati vs Princeton

- A contest between Princeton and the Frascati Laboratories started. Princeton chose a eight-shaped structure: two circular rings in which electrons and positron were circulating with the same orientation, meeting at the collision point. Frascati was even more audacious: they used a single ring with "counter-rotating" beams of electrons and positrons. Although it started for last, it came first: it was 1960, when the era of the colliders has begun. This success had great prominence internationally..

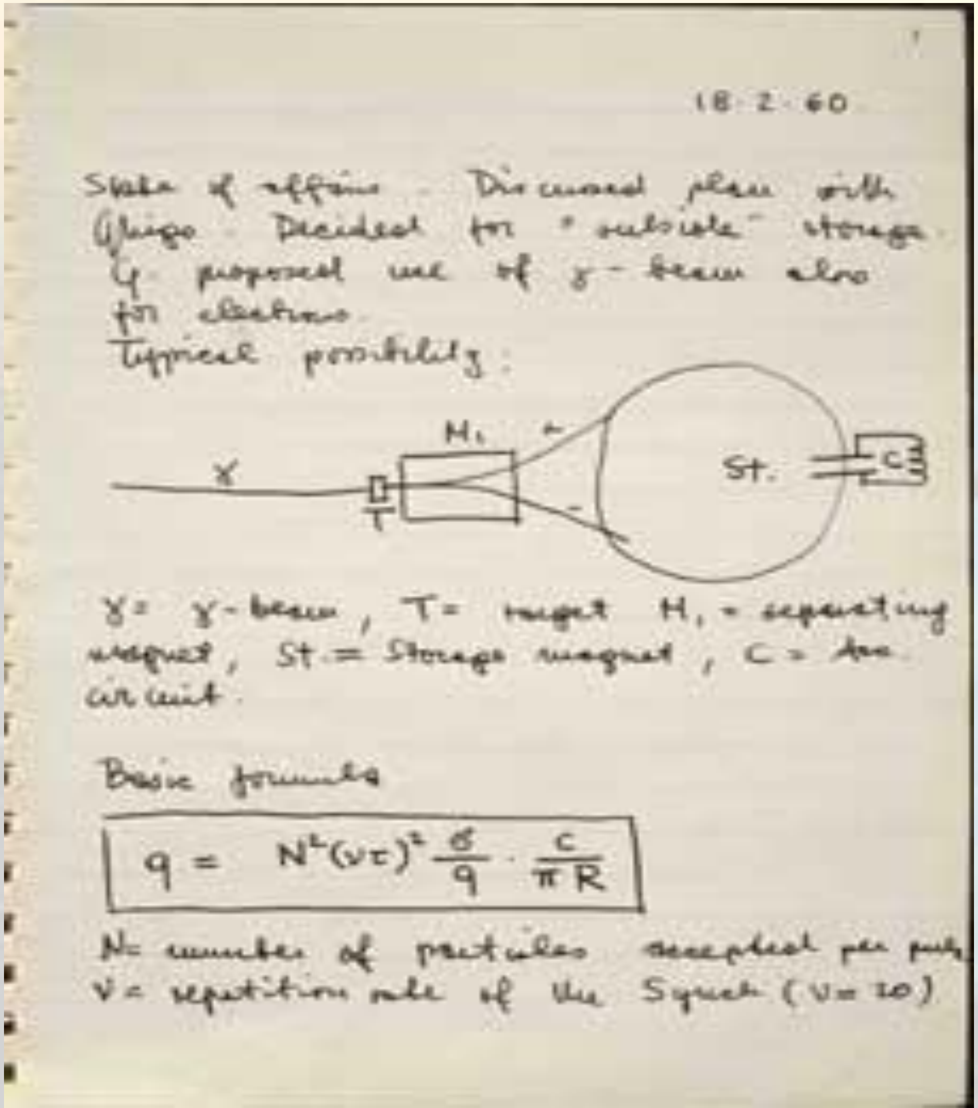
The Contest: Frascati vs Princeton

The enterprise began on March 7, 1960. When Bruno Touschek, who had chosen to live a sunny country, held a seminar at Frascati Laboratories by which he was proposeding to build an electron-positron storage ring, according to Wideroe's visionary ideas concerning storage rings and colliders. On March 14, a preliminary study demonstrated the feasibility of the proposal. The storage ring was called ADA (Anello Di Accumulazione = storage ring).

The total cost of the project (converted from Liras) was around 4.000 €.

The Contest: Frascati vs Princeton

A page from Touschek's notebook


18.2.60

State of affairs. Discussed plans with Ghigo. Decided for "[illegible]" storage. G. proposed use of γ-beam also for electrons.
Typical possibility:

γ = γ-beam, T = target, H1 = separating magnet, St. = Storage magnet, C = [illegible] circuit.

Basic formula

$$q = N^2(\nu\tau)^2 \frac{\sigma}{q} \cdot \frac{c}{\pi R}$$

N = number of particles accepted per puls
ν = repetition rate of the Synch (ν = 20)

ADA

- TOUSCHEK
- Not just a scientist…

Thank you, and keep up the good work

In 1969, when Wilson was in the hot seat testifying before the Congressional Joint Committee on Atomic Energy, Sen. John Pastore demanded to know how a multimillion-dollar particle accelerator (the Fermilab accelerator) improved the security of the Country.

Senator: "Is there anything connected with the hopes of this accelerator that in anyway involves the security of the Country?"

Wilson: "No, Sir. I don't believe so."

Senatord: "Nothing at all?"

Wilson: "Nothing at all."

Senator: "It has no value in that respect?"

Wilson: "It has only to do with the respect with which we regard one another, the dignity of man, our love of culture. It has to do with: Are we good painters, good sculptors, great poets? I mean all the things we really venerate in our Country and are patriotic about. **It has nothing to do directly with defending our Country except to make it worth defending**."