History of Particle Accelerators

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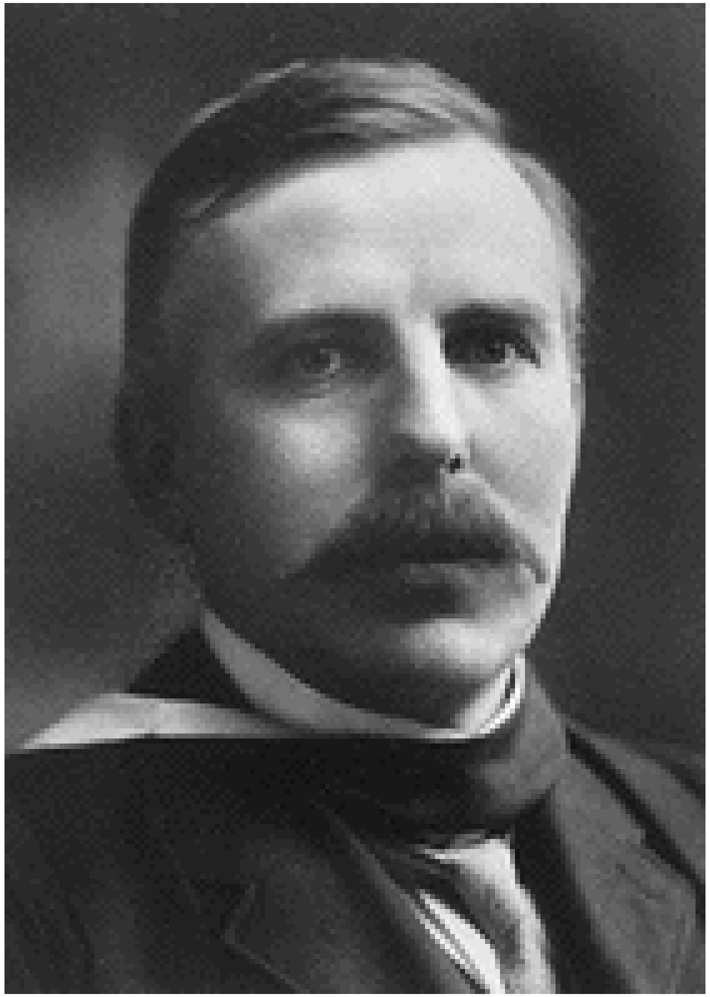
The First Birth

- When speaking of the birth of particle accelerators and high-energy physics, **Ernest Rutherford** is frequently named as the father:

- Born 30 August 1871 in Nelson, New Zealand.
- Died in Cambridge, UK in 1937.
- Professor of physics at McGill University, Montréal (1898-1907).
- Professor of physics at University of Manchester, UK (1907-1919).
- Professor of experimental physics and Director of the Cavendish Lab., University of Cambridge, UK.



The story …

- In 1906, Rutherford bombards a mica sheet with natural alphas of a few MeV and monitors the scattering. In 1919 he induces a nuclear reaction.
- Rutherford believes that he needs a controllable source of many MeV to continue his research on the nucleus and this is far beyond the electrostatic machines then existing, but in …
- **1928 George Gamov predicts quantum 'tunnelling' and perhaps 500 keV would suffice ?**
- 500 keV appeared feasible and so a project for the first accelerator for physics research was launched at Cavendish Lab., UK.
- In 1928, encouraged by Rutherford, John Cockcroft & Ernest Walton start designing an 800 kV generator. By 1932 the generator reaches 700 kV and Cockcroft & Walton split the lithium atom with protons of only 400 keV. **They receive the Nobel Prize in 1951**.

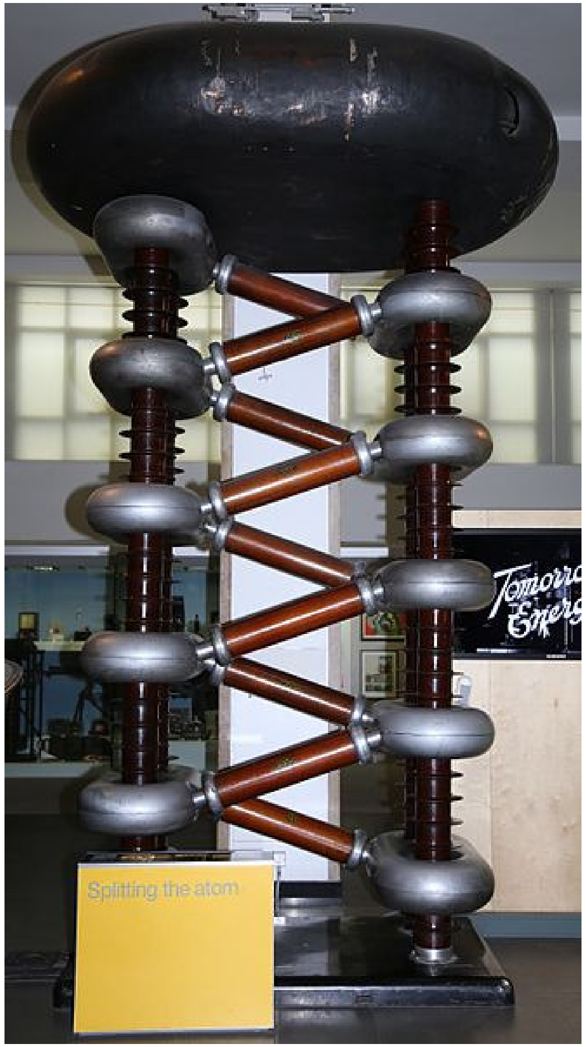
The pros and cons …

- As an engineering solution, the **Cockcroft-Walton Generator** was reliable, robust and highly successful.

- For the next four decades, every accelerator complex around the globe had a Cockcroft-Walton Generator as its front end.

- **This is a textbook example for management. The need was identified, the equipment was built, the desired result was obtained, the solution became a *de facto* World standard and even the Nobel Prize was awarded.**

  But it lacked the potential for higher energies …

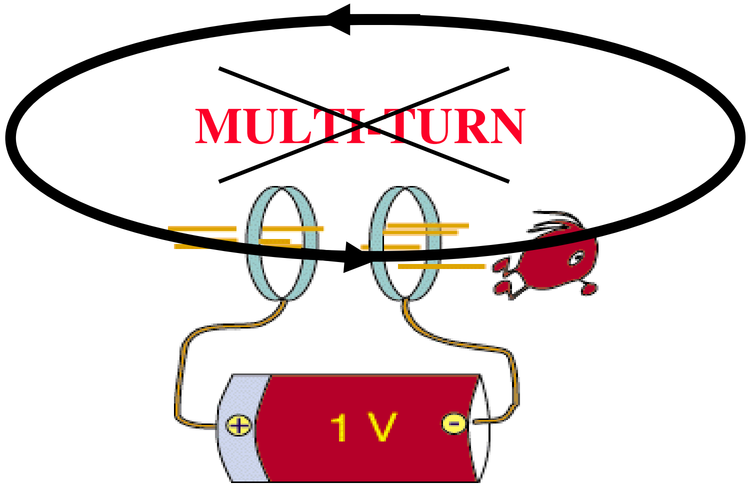


Cockcroft–Walton generator in the London Science Museum - WikiMedia Commons

The drawback …

- The drawback of the Cockcroft-Walton Generator was the impossibility of accelerating ions beyond the maximum voltage in the system*. One could say that it was not a **true** accelerator.

- **The solution to this problem had already been proposed by Ising, but Rutherford was either unaware of it, or he felt that too much R&D would be needed to produce a useful system.**



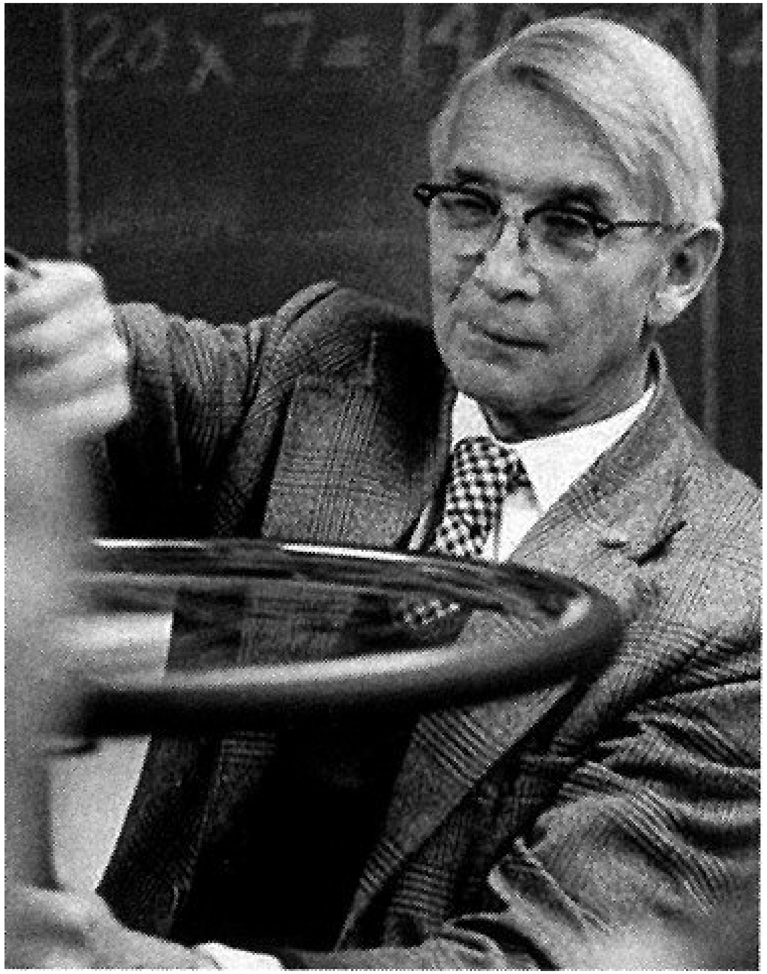
DC generators produce conservative fields and the voltage can only be used once for acceleration.

* There is a clever trick using negative ions to 'cheat' the system into using the applied voltage twice, but the use of static fields to accelerate ions to high energies is still a non-runner.

The second birth

- If we define a **true** accelerator as accelerating charged particles beyond the highest voltage in the system then **Gustav Ising** is the father of today's big (resonant) accelerators :

- Born 19 February 1883 in Finja, Sweden. Died 5 February 1960 in Dandervd.
- Obtained his first degree at Uppsala in 1903 and his PhD at Stockholm in 1919. He became a full professor in 1934.
- He was elected to the Swedish Academy of Sciences in 1935 and served on the Nobel Committee of Physics from 1947–1953.



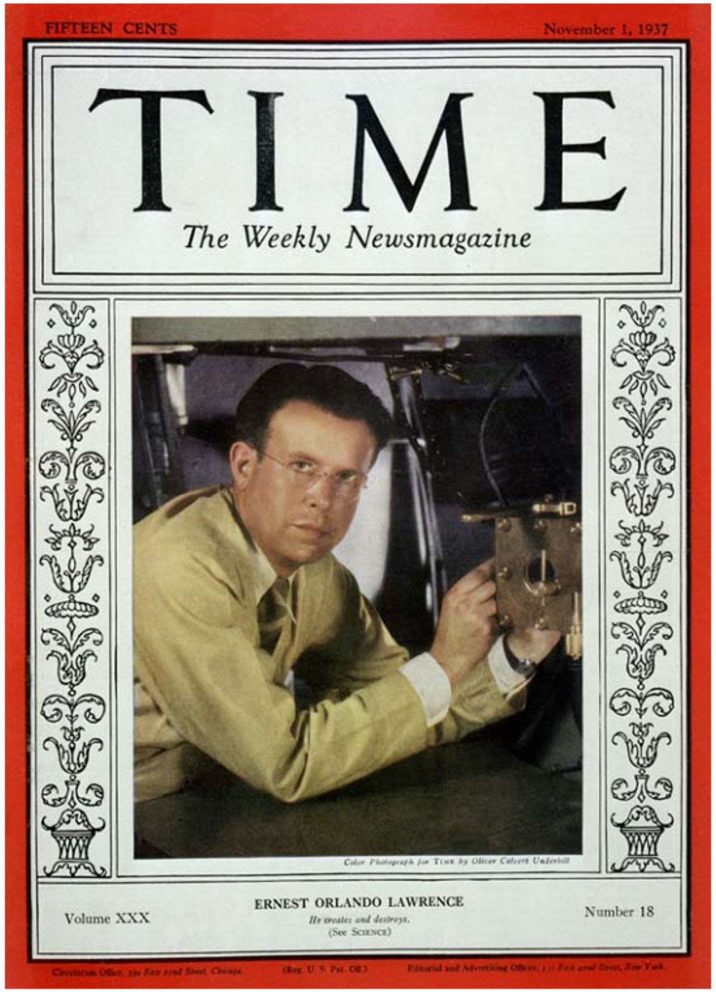
The short story …

- In 1924, Gustav Ising proposes time-varying fields across drift tubes as an acceleration mechanism. This is a **true** accelerator that can achieve energies above the highest voltage in the system.
- In 1928, Rolf Widerøe (a Norwegian PhD student in Aachen) demonstrates Ising's principle with a 1 MHz, 25 kV oscillator and makes 50 keV potassium ions; the **first linac**.
- In 1929, Ernest Lawrence (in the USA), inspired by Widerøe and Ising, conceives the **cyclotron**; a 'coiled' linac and, in 1931, Stanley Livingston demonstrates the cyclotron by accelerating hydrogen ions to 80 keV.
- In 1932, Lawrence's cyclotron produces 1.25 MeV protons and he splits the atom just a few weeks after Cockcroft & Walton. Lawrence received the Nobel Prize in 1939.
- **This tale also appears slick and efficient with the bonus that it stems from an extremely important theoretical invention. The fuller story is more confused and serendipitous.**

The father of the cyclotron …

- **Ernest Orlando Lawrence** is known as the father of the cyclotron, but his involvement was almost an accident and there were other would-be fathers :

- Born 8 August 1901 in South Dakota, USA. Third generation Norwegian. Died 27 August 1958.
- Obtained his first degree in 1922 from the University of South Dakota and his M.Sc in 1923 from Minnesota. He spent a year at the University of Chicago and then moved to Yale, where he completed his Ph.D in 1925 on the photo-electric effect and become assistant professor in 1927.
- During the 1920s, a study period in Europe was considered essential for scientific high flyers. However, Lawrence was 100% US educated.
- Nevertheless, in 1928, Lawrence was hired as an Associate Professor of Physics at the University of California, and two years later he became the youngest full professor.



The fuller story …

- Lawrence saw (early 1929) Widerøe's article in *'Arkiv für Electrotechnik'* and was inspired to build a cyclotron.
- **Yes, but it seems he had taken the journal to pass the time in a boring meeting** and with the possible intention of looking at an article by Rogowski on Kerr cells – a subject closer to Lawrence's work at that time. **Moreover, he did not speak German and was limited to looking at diagrams and equations.**
- Lawrence was slow to react possibly because this represented a significant change from his earlier work. It was Otto Stern who finally encouraged him into action.
- His first graduate student, Niels Edlefsen, was only partially successful and it fell to a second student, Stanley Livingston, who was looking for a PhD topic, to provide the proof-of-principle cyclotron.

Another father of the cyclotron …

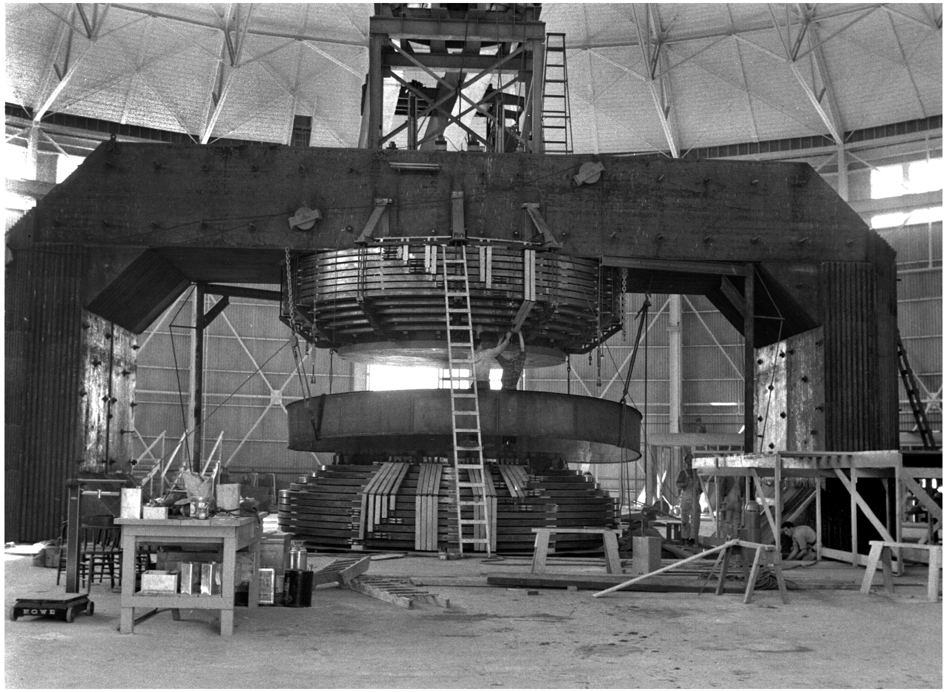
- **Jean Thibaud** was a young physicist in Maurice de Broglie's lab. in Paris, who (like Rutherford) was also impatient with natural radioactive sources. He uses the ideas of Ising to reach 145 keV after passing positive ions through no less than 11 rf gaps driven at 3 MHz. His aim was to reach 10 MeV.
- Realising the practical problems of a linear structure, Thibaud built a cyclotron and in 1932 claimed observation of the 'resonance condition' before Lawrence at Berkeley.
- Lawrence was in contact with Thibaud after the 1933 Solvay Conference, but lack of support and encouragement from Thibaud's bosses stopped all cyclotron work in France.

And more would-be fathers …

”Success has many fathers, while failure is an orphan”

- **Denis Gabor** claimed to have thought of the cyclotron in 1924, but was too busy to act at the time.
- **Eugen Flegler**, a colleague of Widerøe, had proposed the use of a magnetic field as early as 1924, but was discouraged by Widerøe over doubts about orbit stability.
- On January 5 1929, **Leo Szilard** filed a patent for a cyclotron and contacted Gabor, who was working for Siemens at the time, but Gabor (Siemens?) took no further action.
- **Max Steenbeck** recounts that during his PhD (1927) he solved a numerical problem for a student for what was essentially a 20 cm 1.4 T cyclotron. Later Steenbeck went to work for Siemens and was encouraged to write up his idea, but his chief returned the manuscript requesting to see Steenbeck. The latter felt that this was a rejection and Siemens lost the cyclotron for a second time.
- **The last word lies with Szilard who said *“The merit lies in the carrying out and not in the thinking out of the experiment”*.**

184 inch cyclotron …



Lawrence's largest cyclotron,

the 184 inch under construction 1942

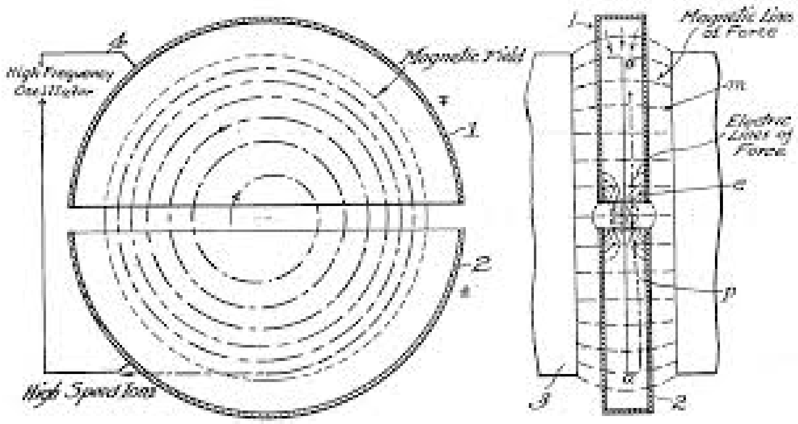


Diagram from Lawrence's patent application for the cyclotron, granted 2/2/1934.

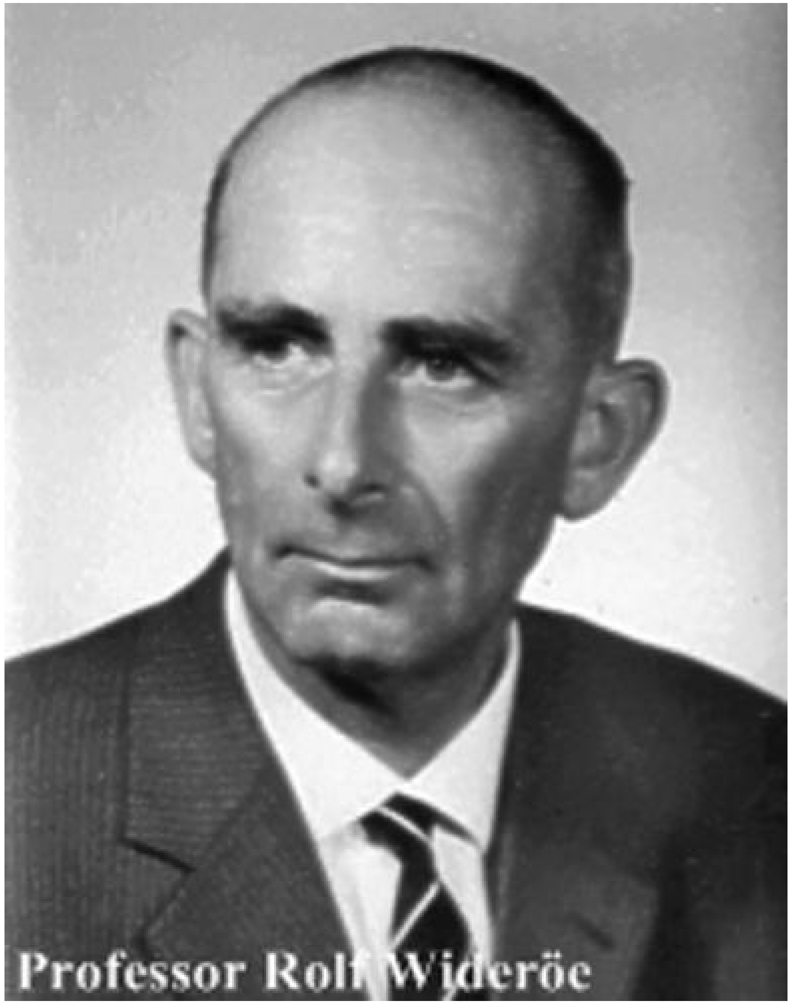
Lawrence was pushed into taking this patent as a part of a deal to get more funding. The Europeans had missed the opportunity to patent several times partly because Wideröe had given his private opinion that the cyclotron would never work. Eric Baron in a Ganil report says that Lawrence was lucky not to have known Wideröe's opinion, or he might never have tried.

The drawbacks …

- The cyclotron was the leading machine in high-energy physics in the 1930s and 40s. The synchro-cyclotron extended this period slightly, but the proton synchrotron became the preferred high-energy machine in the 1950s. By the 1980s, cyclotrons were firmly rooted in industrial and medical applications.
- The cyclotron energy is limited primarily by relativistic effects.
- The second limitation is the mass of the magnetic circuit.
- The third is the difficulty of providing sufficient focusing.
- A lot of development has gone into synchro-cyclotrons, sector-focused cyclotrons, super-conducting cyclotrons, etc., but the lack of potential for GeV energies is decisive for HEP.
- **Before moving to the next step in accelerator development, we must visit a third candidate for the first birth.**

The third birth

- **Rolf Widerøe** pre-dates Ising with the invention of another **true** accelerator, the **betatron** (a non-resonant accelerator). We have already seen his name. He demonstrated Ising's proposal for resonant acceleration for his PhD :
- Born 11 July 1902 in Oslo, Norway.
- Died 11 October 1996 in Obersiggenthal, Switzerland.
- Gained his PhD at the Technical University of Aachen.
- He made over 200 patent applications many in the field of particle accelerators.



The story …

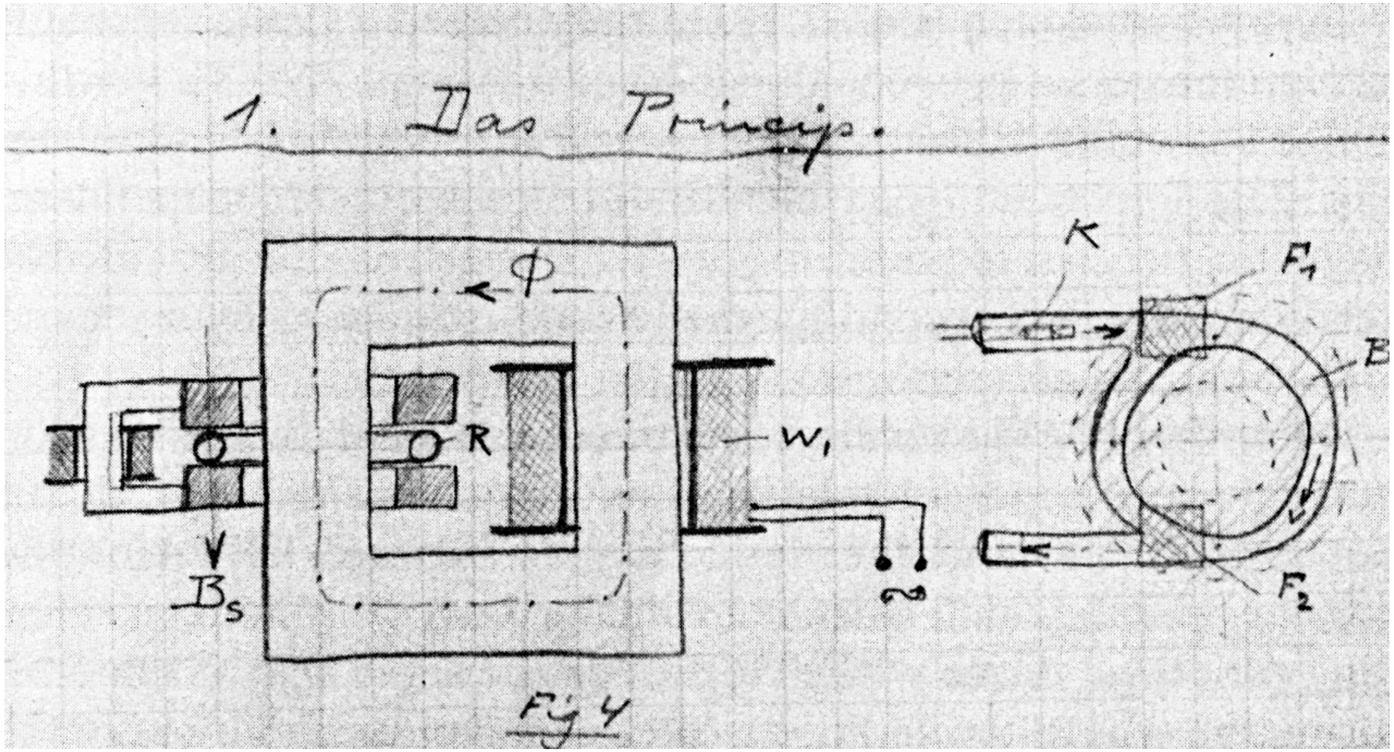
- In 1923, Widerøe, a young student, draws in his laboratory notebook the design of the **betatron** with the well-known 2-to-1 rule. He adds the condition for radial stability 2 years later, but does not publish.

- In 1927 in Aachen, Widerøe makes a model betatron, but it does not work. Discouraged, he changes course and builds the world's first linac (see the second birth). **His betatron lies forgotten in his drawer.**

- All is quiet until 1940, when Donald Kerst re-invents the betatron and builds the first working machine for 2.2 MeV electrons (University of Illinois). In 1950, Kerst also builds the world's largest betatron (300 MeV).

- **Widerøe was truly a great founding father of accelerators. His name was put forward for the Nobel Prize, but this was unsuccessful.**

The Betatron …

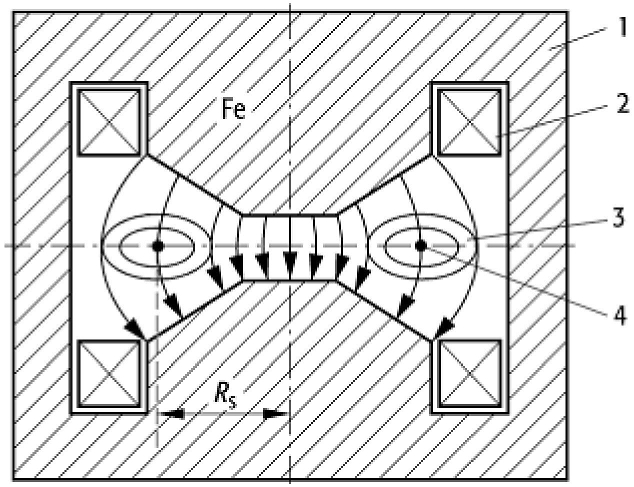


Widerøe called this device a “Strahlung Transformator” because the beam effectively forms the secondary winding of a transformer. The above diagram is taken from his unpublished notebook (1923). This device is insensitive to relativistic effects and is therefore ideal for accelerating electrons. It is also robust and simple.

Drawbacks …

- The Betatron missed its 'window of opportunity' by being hidden in a laboratory drawer until 1940.
- After a brief spell of interest, it was rapidly overtaken by linacs and synchrotrons.
- Although it is a robust and simple device that is ideally suited to accelerating electrons, it was limited in energy by the size of the magnetic yoke.

Kerst's betatron 1942 Wikipedia



Principle of operation

Magnetic and electric fields

- Accelerators must use electric fields to transfer energy to/from an ion, because the force exerted by a magnetic field is always perpendicular to the motion.

- Mathematically speaking, the force exerted on an ion is:

$$\boldsymbol{F} = e\boldsymbol{E} + e(\boldsymbol{v} \times \boldsymbol{B})$$

so that the rate at which work can be done on the ion is:

$$\boldsymbol{F} \cdot \boldsymbol{v} = e\boldsymbol{E} \cdot \boldsymbol{v} + e(\boldsymbol{v} \times \boldsymbol{B}) \cdot \boldsymbol{v}$$

but

$$(\boldsymbol{v} \times \boldsymbol{B}) \cdot \boldsymbol{v} = 0.$$

- **Each ‘Birth / History line’ can be classified according to how the electric field is generated and used.**

The electric field …

$$\boldsymbol{E} = -\nabla\phi - \partial \boldsymbol{A}/\partial t$$

1st birth

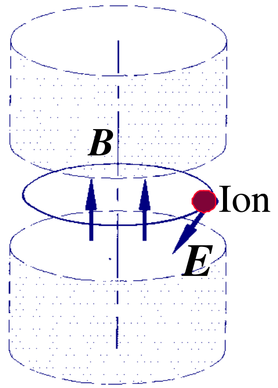
Acceleration by DC voltages:
- Cockcroft & Walton rectifier generator
- Van de Graaff electrostatic generator
- Tandem electrostatic accelerator

Acceleration by time-varying fields:

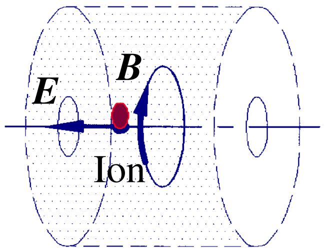
$$\nabla \times \boldsymbol{E} = -\partial \boldsymbol{B}/\partial t$$

3rd birth

'Betatron' or 'unbunched' acceleration



'Resonant' or 'bunched' acceleration
- Linear accelerator (linac).
- Synchrotron.
- Cyclotron ('coiled' linac).

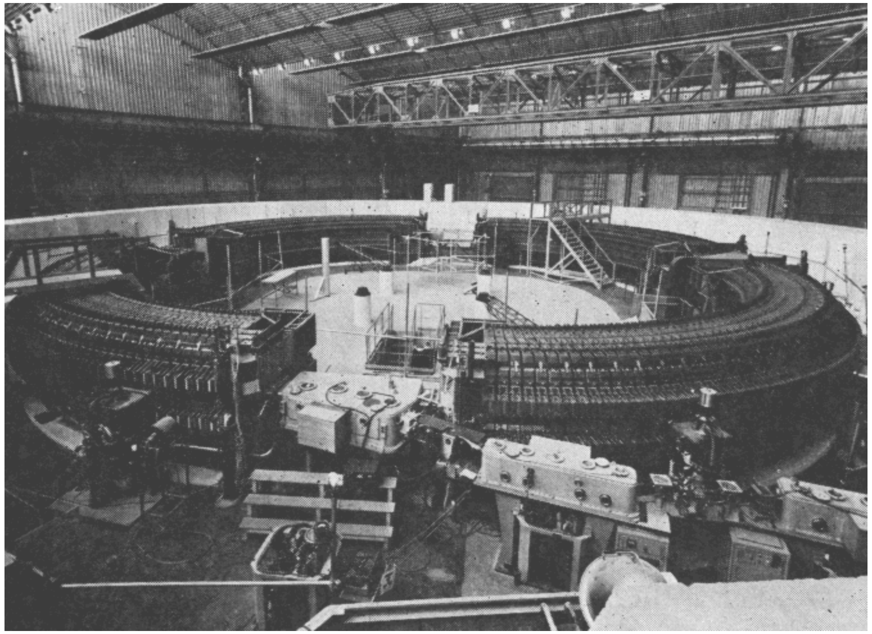


2nd birth

The winner

Synchrotrons

- 1944 McMillan and Veksler independently propose **synchronous acceleration with phase stability**.
- 1946 Goward and Barnes are first to make the synchrotron work in the UK.
- 1947 Oliphant and Hyde start a 1 GeV machine in Birmingham, UK, but an American group overtakes them and is first with the 3 GeV Cosmotron at BNL.
- The early synchrotrons were weak focusing (large aperture) machines with very few and very short drift spaces for injection, extraction and monitoring.

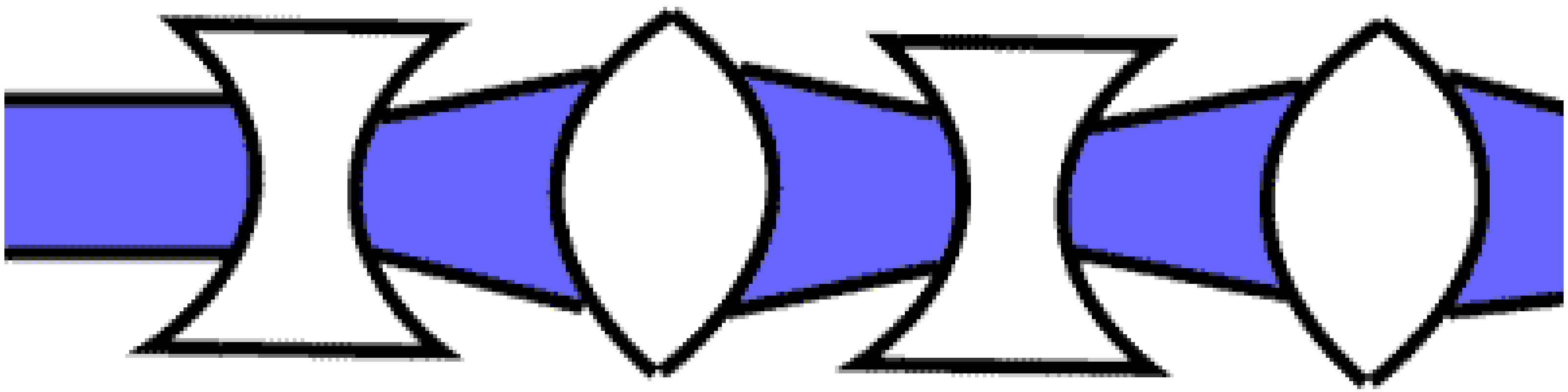


'Saturne', a 3 GeV proton synchrotron at Saclay, commissioned in 1958.

Note the characteristic 'C' shaped cross-section of the long, curved dipole magnets.

Strong focusing

- 1952 Christofilos, and Courant, Livingston and Snyder independently invent **strong focusing**. CERN immediately drops its design for a weak-focusing, 10 GeV FFAG in favour of a strong-focusing, 28 GeV synchrotron.
- Strong focusing brings in the concept of separate-function lattices, reduces the aperture and makes it possible to customize the lattice.



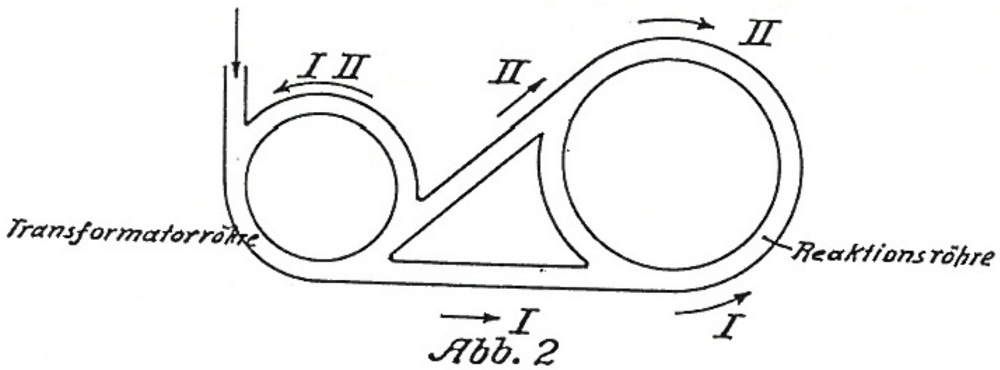
The story of Nicholas Christofilos …

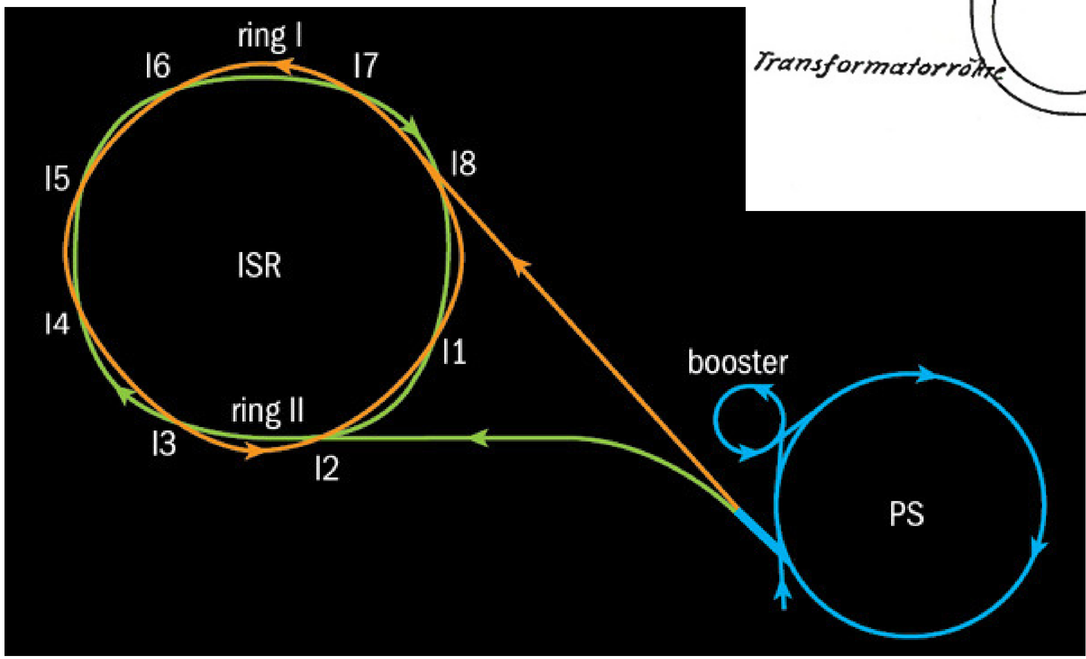
- In 1948, Christofilos was sending the University of California Radiation Laboratory at Berkeley letters with his ideas on accelerators. He received some replies explaining flaws, **but in 1949 the all-important letter containing the invention of strong focusing was put in a drawer and left unanswered.**
- Undeterred, Christofilos applied for a patent in 1950 (granted 1956).
- Meanwhile Courant, Livingston and Snyder independently invented strong focusing at BNL in 1952.
- In 1953, Christofilos confronted BNL, the AEC paid him 10 k$ for his patent and he was credited as the original inventor.
- In the same year, Christofilos unveils his clever new idea for controllable fusion, which later became the ASTRON machine under his leadership at Livermore. Christofilos died in September 1972 and ASTRON closed shortly after, but he is recognised as the inventor of the Reversed Field Concept for fusion.

Colliding beams

- In 1943, Widerøe is again a pioneer and patents circular colliders.
- Owing to the war, the patent is not published until 1953.
- LHC and ISR in CERN use this principle.

Wideroe's patent application.

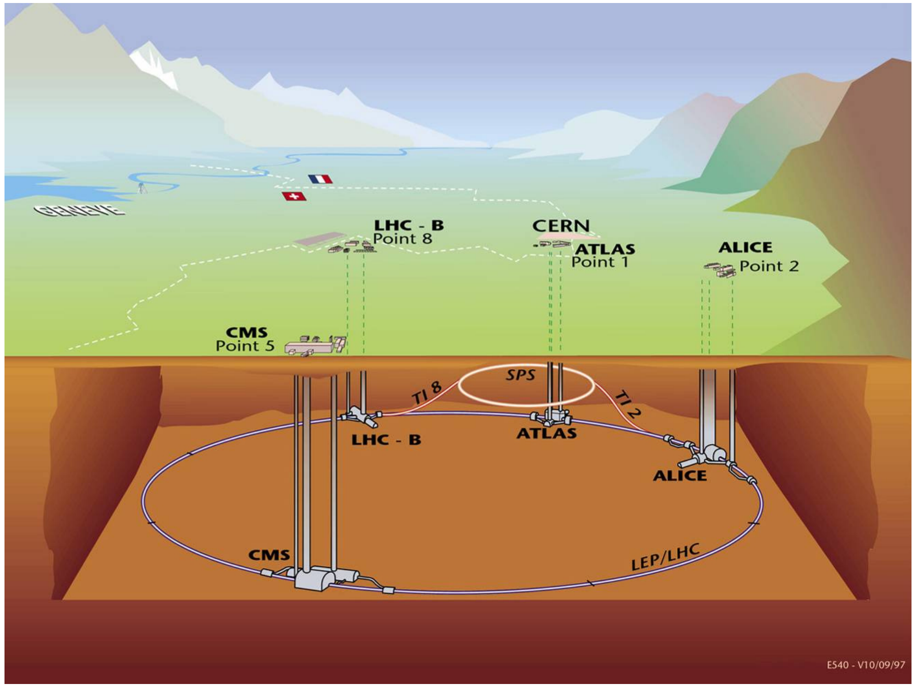




The CERN ISR layout.

Saved by technology and governments

- All the currently-used accelerating methods were known by the early 1940s and all the basic design techniques were known by the 1950s.
- Improvements in beam energy, emittance and intensity however continued unabated thanks to :-
  - **Advances in technology : super-conductivity, fast electronics, new materials.**
  - **The willingness of governments to support ever-larger budgets.**
  - **International collaboration.**
  - **The exo-geographical transition that allowed CERN to build machines underground, under other peoples' property.**

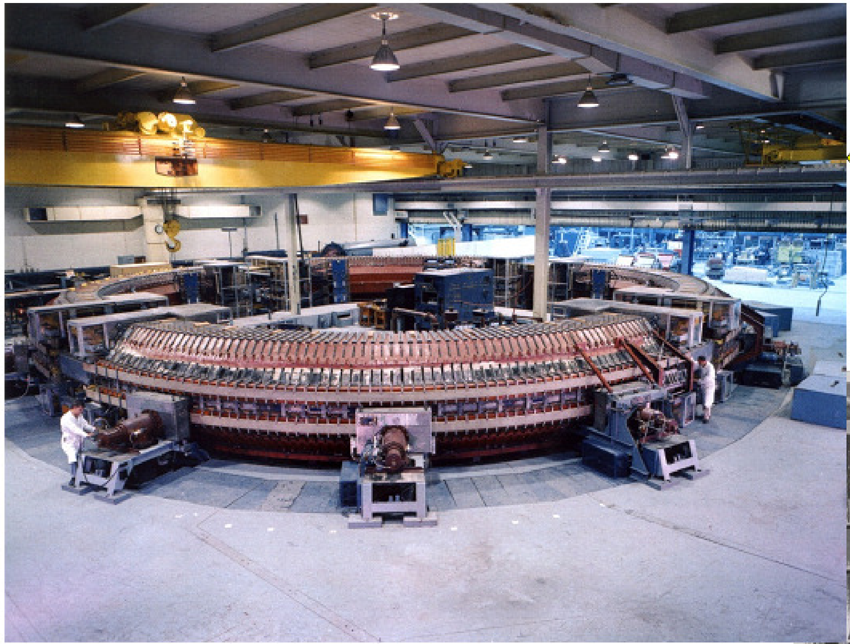


Note: Physics experiments also had to change fundamentally into world-wide collaborations.

The pendulum swings

- In the 1800s and early 1900s, Europe was the scientific and engineering centre of the world and the cradle of particle accelerators.
- But, when Lawrence picked up Widerøe's paper in 1929, the 'pendulum' for accelerators started its swing from Europe to the US.
- Lawrence founded the Radiation Laboratory of the University of California, on 26 August 1931 for his cyclotron research. This became the world-leading **Lawrence Berkeley National Laboratory**.
- In 1947, the **Brookhaven National Laboratory** was founded on the US east coast on Long Island. At that time, Europe had just been devastated by war and only Britain had its research laboratories intact.
- **There was one bright hope for Europe.** The convention for a European laboratory called **CERN** was ratified on 29 September 1954 by 12 countries in Western Europe, but CERN was too new to compete with the established US labs.

Europe slips behind the US



Cosmotron (BNL) 3 GeV (1952)

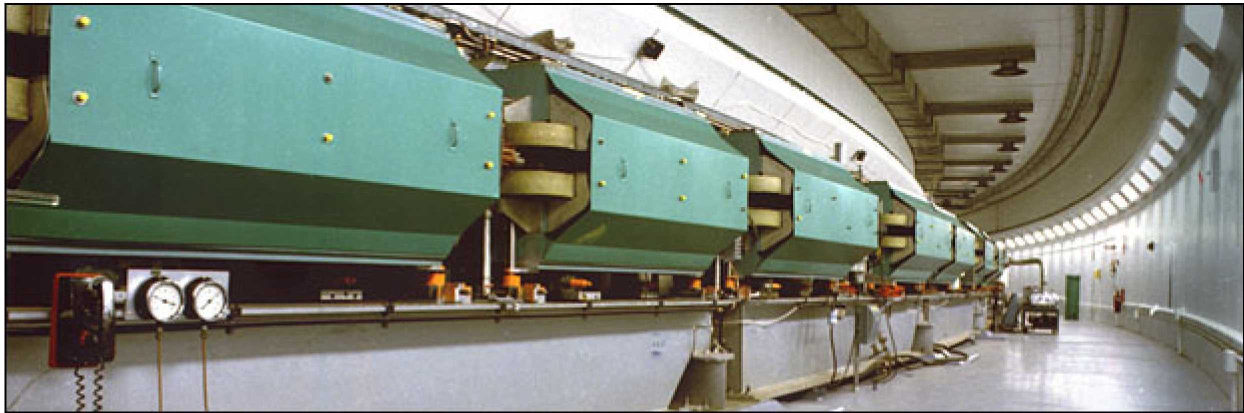
Livingston, Blewett(s), Courant, Green & Blackburn

Birmingham 1 GeV (1953)

Oliphant

Slide borrowed from : Ken Peach; Partner Course at CERN; 3/3/2012; slide 56.

CERN fights back …



AGS-BNL 33 GeV

1960

CERN-PS 28 GeV

1959

USA leads the accelerator world

- By 1967, when **Fermilab** (Fermi National Accelerator Laboratory) was founded at Batavia, Illinois, near Chicago, the ‘pendulum’ had swung fully to the US.
- The original main ring accelerator at Fermilab (6.86 km circum. with conventional magnets) was completed in June 1971. The beam energy reached the design value of 200 GeV by March 1972 and with upgrades reached 500 GeV by 1976 when the name was changed to the now famous **Tevatron**.
- With a major superconducting magnet upgrade, the Tevatron beam energy reached a world-beating 900 GeV in 1983 and, by operating the accelerator as a proton-antiproton collider, collision energies of 1.8 TeV were obtained.
- The addition of an injector ring and upgrading low-beta insertions made it possible to progressively increase the luminosity of the collider. **From 2004 until September 2011, the Tevatron was both the highest energy and highest luminosity collider in the world.**

Fermilab and the Tevatron …

But all is not well …

- Behind the success of the Tevatron, difficulties were being experienced with the **SSC** (Superconducting Super Collider) that was intended as the next-generation, world-beating machine.
- The SSC was to be built in Texas with a circumference of 87.1 km and 20 TeV per beam (much bigger and more powerful than the present CERN LHC).
- Partly to avoid redundancy and partly in the hope of freeing resources for the SSC, the US high-energy physics community sacrificed another superconducting collider project called ISABELLE for a 200 GeV per beam collider at BNL, Long Island.
- **Unfortunately, the cancellation of ISABELLE (July 1983) served more as a dangerous precedent for the closure of the SSC.**
- With the cancellation of the SSC in October 1993, the pendulum was rapidly swinging back to Europe.

The pendulum returns to Europe

- Write-off on closure of ISABELLE (1983) ≈ 0.2 billion US dollars
  Write-off on closure of the SSC (1993) ≈ 2 billion US dollars,

  and the southern part of Dallas–Fort Worth Metroplex went into a mild recession.
- Against the background of the US write-offs, the CERN Member States had the courage to approve the **Large Hadron Collider (LHC)** in December 1994.
- The LHC was able to make a considerable financial saving by using the existing 27 km long LEP tunnel, which limited the LHC to 7 TeV beams.
- The LHC eventually cost about 5 billion US dollars to build and began operation 10 September 2008.
- The Tevatron ceased operations on 30 September 2011, due to budget cuts and competition from the more powerful LHC.
- **The 'pendulum' was firmly back in Europe.**

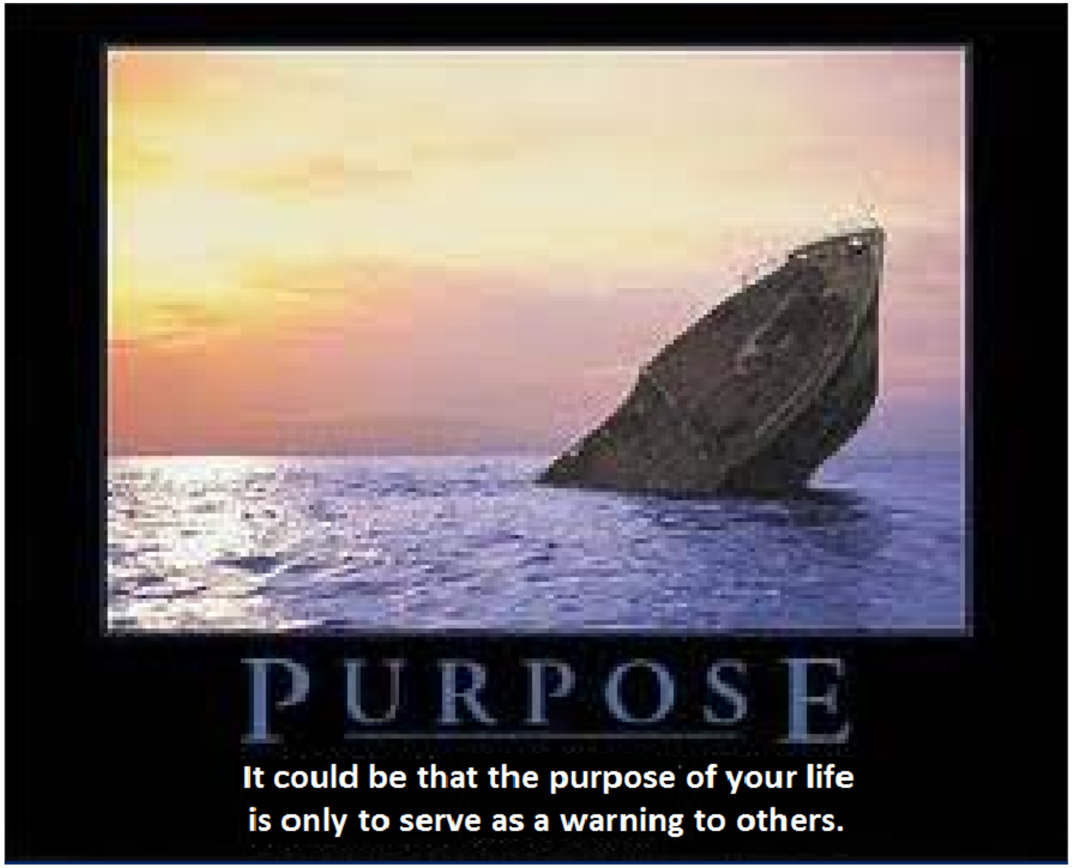
Feelings run deep …

This illustration was included in an interim report to the US Department of Energy (DOE), Accelerator Task Force, by N. Holtkamp, SLAC in March 2012.

The subject was

Accelerators for America's future,

Workshop 2009.



Funding for research

- From the earliest times philosophy, mathematics and science were the domain of universities, private fortunes and patronage.
- After the World Wars research had become too expensive for individuals and the attitude of the general public to science had changed, following events such as Hiroshima (6/8/1945).
- Alerted to the importance of research by the World Wars, governments continued to fill the breach and funded yet more and more research.
- From 1945 to the 1970s, the attitude towards funding **basic research** was generally favourable in most industrial nations.
- A celebrated report published in 1945 by a group led by Vannevar Bush, the US presidential Science Adviser, entitled “Science – The Endless Frontier” argued that money spent on basic research would, sooner or later, contribute to wealth, health and national security, and that one should not worry too much about exactly what form these benefits might take, and when they might occur.
- Until the end of the 1960s public funding for basic research grew appreciably in real terms year by year.

Funding for research …

- The attitude of Governments was however changing. They wanted more tangible returns from basic research.
- It has been suggested that in the US in the1950s, there was a tacit understanding that if the government kept university scientists happy by funding their research, then those scientists would be available to help in the case of war. However, the Reagan administration tried unsuccessfully to cash this tacit cheque when seeking support for the ‘star wars’ initiative.
- In the 1970s, the UK was first to come under severe stress from rising public expenditure.
- Laboratories were told to do **‘useful’ applied research** to help support their own basic research. Soon business plans, innovation, patenting, spin-off companies, technology transfer etc. became the new buzz words for getting Government approval.
- **Today, amid the numerous schemes to help would-be innovators and entrepreneurs, one has the feeling that there are more advisors and coordinators than workers.**

The challenge

- How far is beyond?
  - The CERN LHC will operate at 2×7 TeV.
  - The cosmic ray spectrum is expected to extend up to the Planck energy (1.22×10^{28} eV), but cosmic rays above 5×10^{7} TeV from sources beyond 1.5×10^{8} light-years will be absorbed by photons of the microwave background (GZK cut-off).
- Today's accelerators are nearing practical limits. What can be done?
  - 1982 ECFA held the first workshop of a series on advanced accelerating techniques; 'Challenge of Ultra-high Energies", New College, Oxford, UK.
  - The goal was a new acceleration technique capable of PeV energies at a reasonable cost.
- Four essential ingredients are:
  - A new acceleration mechanism.
  - Transverse stability.
  - Longitudinal (phase) stability.
  - Stability against collective effects.
- The candidates are:
  - Plasma-beat-wave accelerator.
  - Wake-field accelerator.
  - Lasers with gratings.
  - Lasers on dense bunches.
  - But the search is still on.

For the next generation we would like 1 TeV on a table top and 1000 tables (1 PeV). This is the challenge.

Thank you for your attention.