Industrial applications of advanced superconductivity

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Senator for life of the Italian Republic

Introduction

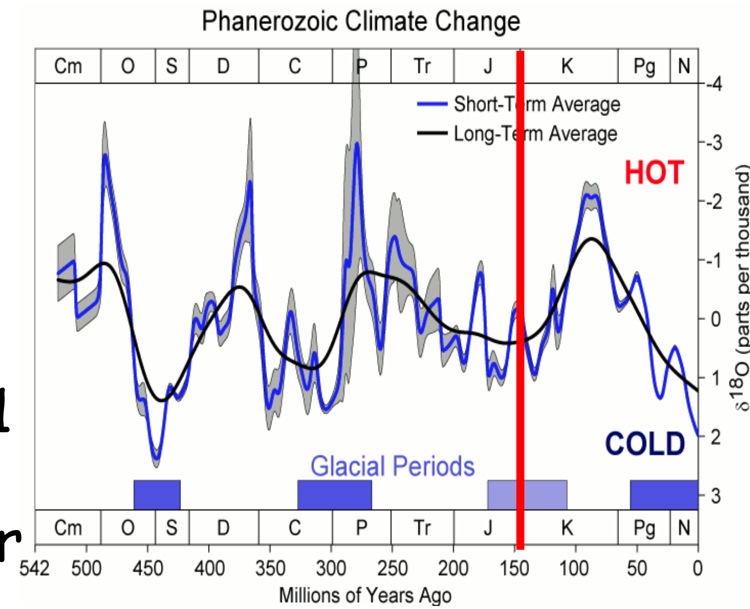
- On a human time scale of Ka (*Kilo-annum*, thousand years) planet motions are a model of remakable regularity.
- However on longer times, planets are chaotic, resulting in future unknown orbital paths and eventually leading to a severely disrupted solar system.
- For instance, while in a *regular* region two planetary trajectories that begin arbitrarily close in phase space will diverge as a power (usually linear) of the elapsed time, in a *chaotic* region nearby trajectories will separate out exponentially.
- A typical error of 15 m in the Earth's initial position after 10 Ma (*Mega-annum*, million years) brings to an error of about 150 m; but the same error may grow after 100 Ma to 150 million km, making impossible the precise prediction of the orbits.

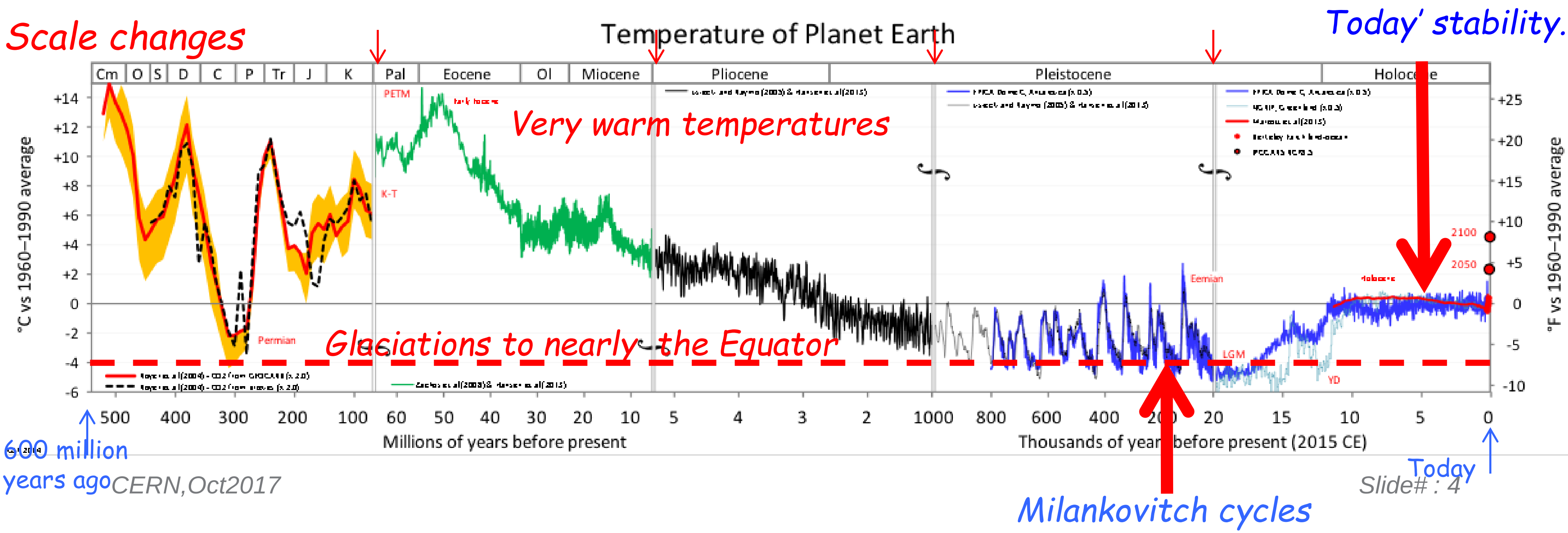
The early “Snowball” Earth

- 4.54 Ga ago, the Sun as a Main Sequence star radiated only 70% of the current energy. The luminosity has been rising by 1% every 110 Ma. But, although the temperature of the Sun kept rising, Earth did not get warmer*: rather it cooled dramatically*.
- Earliest undisputed evidence of life are *microbial methane fed fossils* such as stromatolites found in 3.48 Ga sandstones.
- After exposed minerals were oxidized between 2,5 and 2.3 Ga, Oxygen finally began to accumulate in the atmosphere.
- Glacial deposits in South Africa dated 2.2 Ga and located then at the Equator *showed the Earth as totally frozen* .
- The ice age around 2.3 Ga may have been directly caused by the increased Oxygen concentration in the atmosphere, which caused the decrease of methane (CH_4) in the atmosphere.
- There were four periods, each lasting about 10 million years, between 750 and 580 million years ago, with the Earth thought to be totally *covered with ice and at a temperature of -50 ° C*

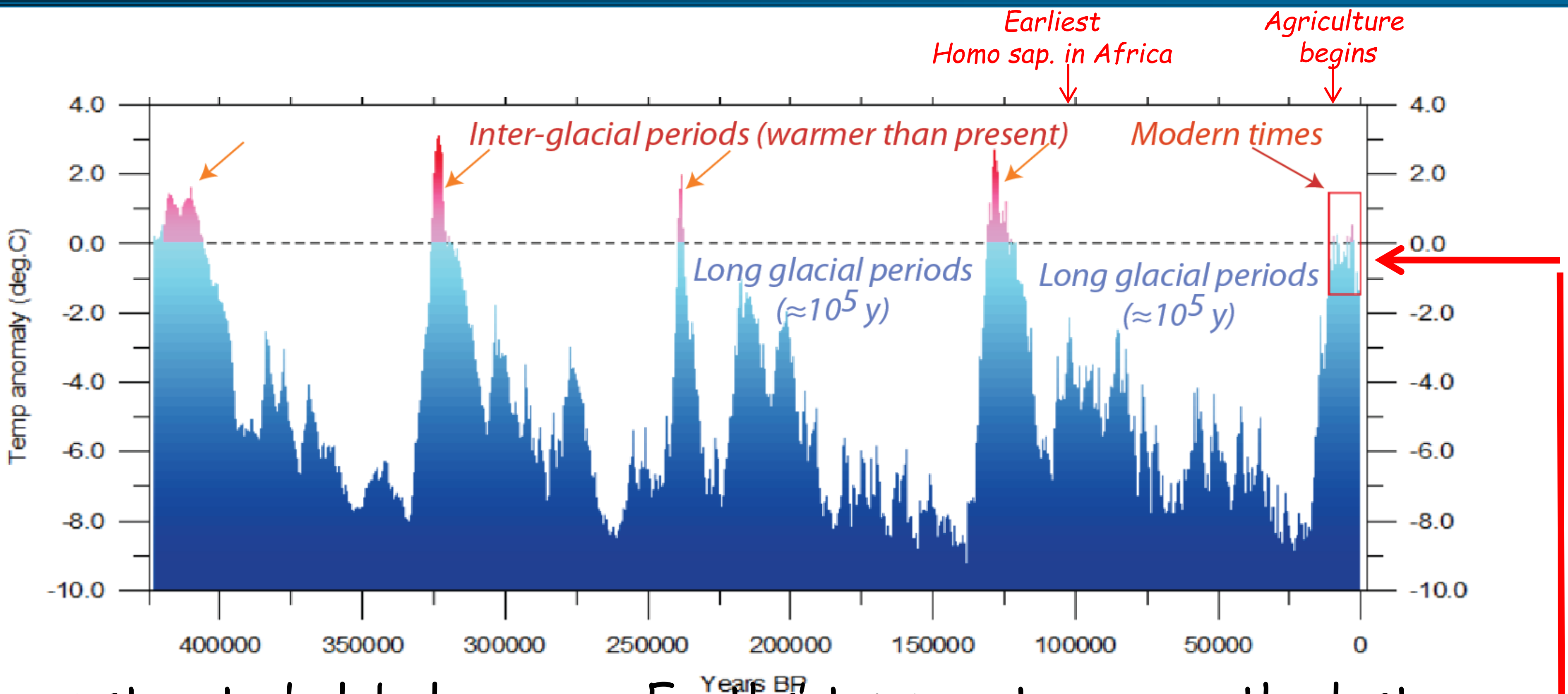
The last 600 milions of years

- The Phanerozoic era, the *origin of multi-cellular life 600 Ma ago,* has been as well characterized by a series of cycles between glaciations and warmer temperatures.
- There have been about four of such cold cycles separated by about 140 million years. The earlier Neo-proterozoic era (1000 to 541 millions of years ago) shows also important glaciations with oceanic ices up to the equator



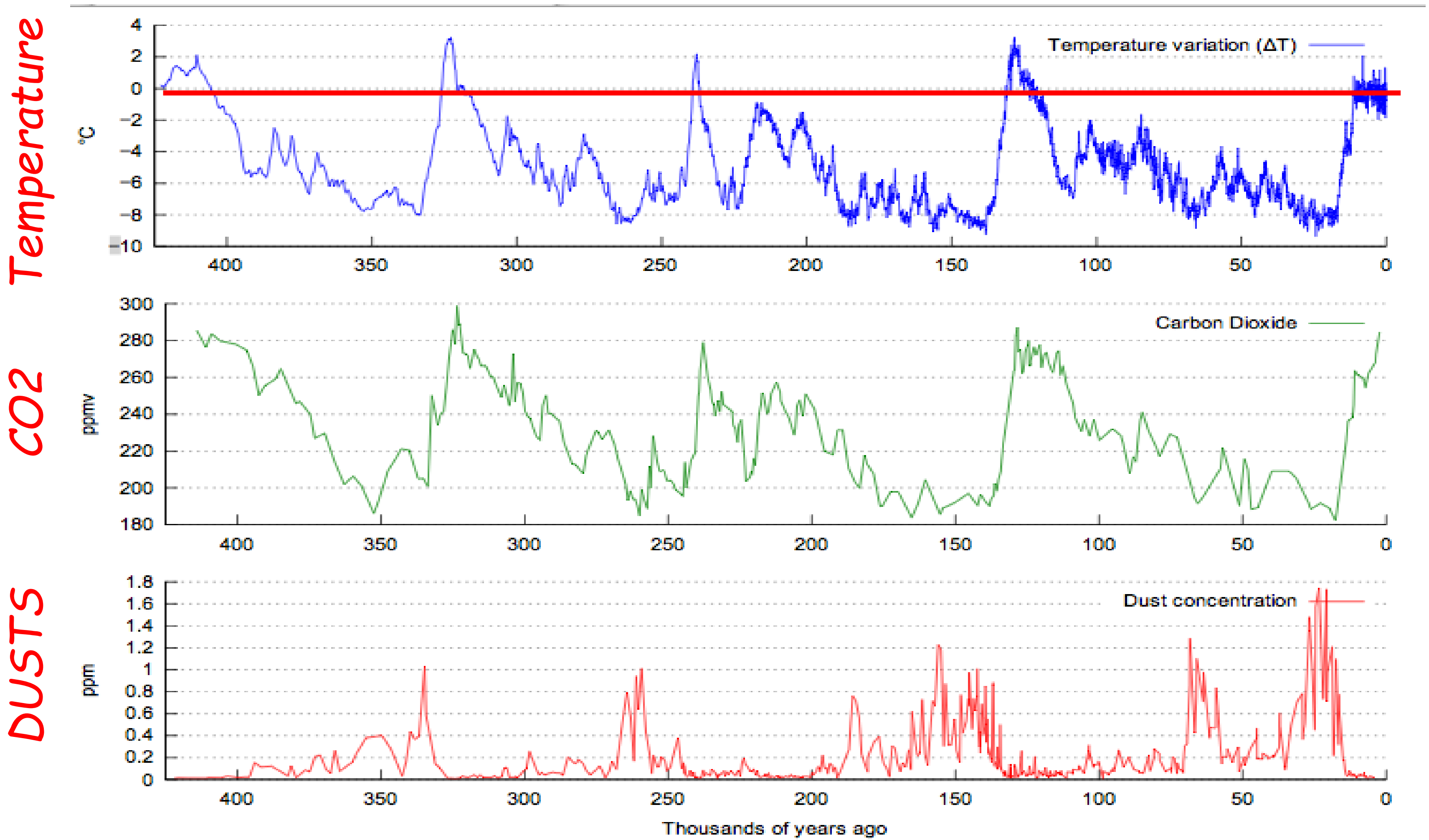


Global average temperature during the last 0.4 Million years



- Reconstructed global average Earths' temperature over the last 420'000 years based on the Vostok ice core from the Antartica (Petit et al. 2001) as measured from the O^{18} global concentration
- The five short warm periods (shown in red) have been exceptional, lasting only for a relatively short periods between long glacial periods of $\approx 10^5$ years.

Data from Petit et al.



- Graph of CO_2 (green), reconstructed temperature (blue) and dust (red) from the Vostok ice core for the past 420 ka.

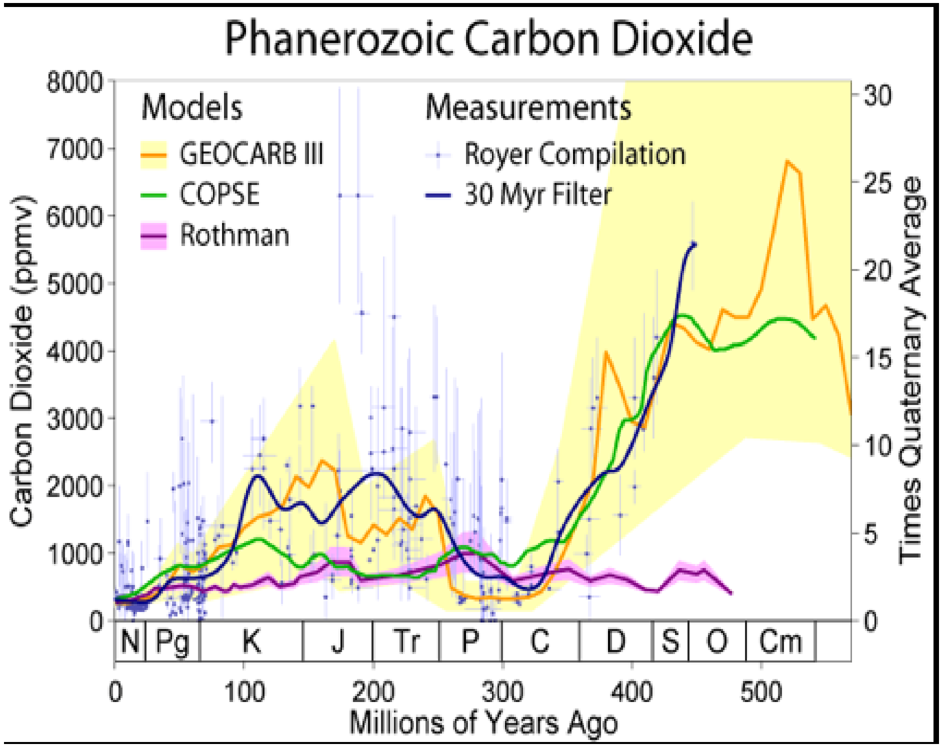
A next glaciation ahead ?

- Now, since about 10 ka Earth is in the Holocene interglacial period.
- *The present warm period would normally be expected to last for just a few Ka*. The Milankovitch theory predicts that glacial periods periodically covering the higher latitudes of the continents will occur cyclically because of astronomical factors in combination with climate feedback mechanisms.
- The increased rate of carbon dioxide released by man may slightly delay the forthcoming next glacial period of ≈ 100 ka's duration.
- On the other hand, the present global warming period of finite duration (based on the assumption that fossil fuel use will cease in a few centuries) may probably only impact for about a few ka the arrival of the *next, inevitable Milankovitch glacial period*.
- Thus, our global warming induced through a few centuries worth of greenhouse gas emissions may only have a relatively local impact.

A future but inevitable forthcoming glaciation could be dramatic to the survival of billions of people

Natural accumulations of CO_2 during the last 600 Ma

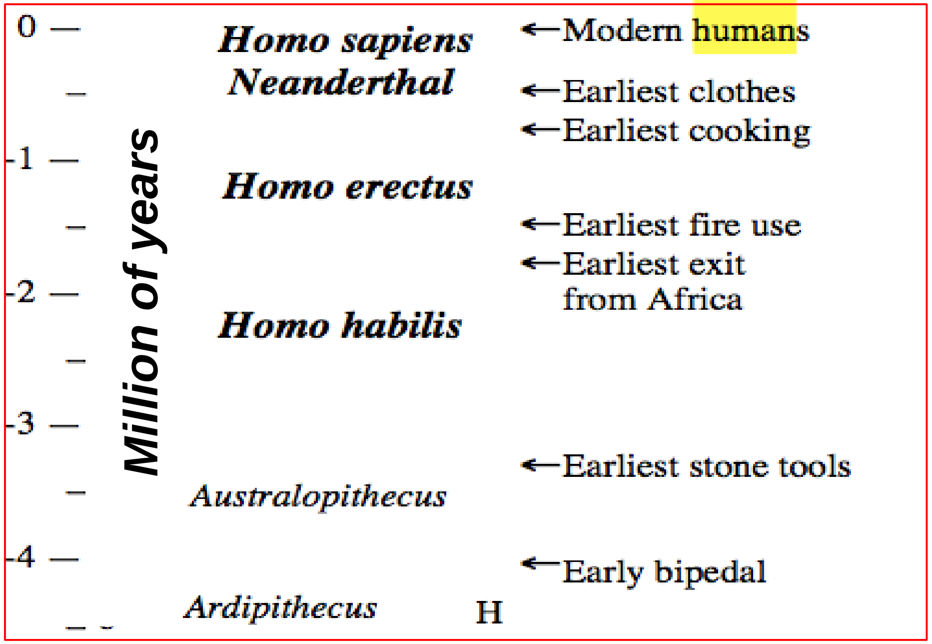
- In the past CO_2 values were many times higher than now, although the exact value may be in doubt. 600 million years ago atmospheric CO_2 was about 20 times higher than present values.
- It dropped, then rose again some 200 million years ago to 4-5 times present levels—a period that saw the rise of giant forests without flowers — and then continued a slow decline until recent pre-industrial time.
- At present, the burning of fossil fuels is the leading cause of an increased CO_2, now at 400 ppmv and rising maybe to 700 ppmv by 2100.
- In 2010, 9.14 GtC of fossils were released compared to 6.15 GtC in 1990.



(History of Atmospheric CO2 through geological time. Berner, **Science**, 1997).

The human evolution

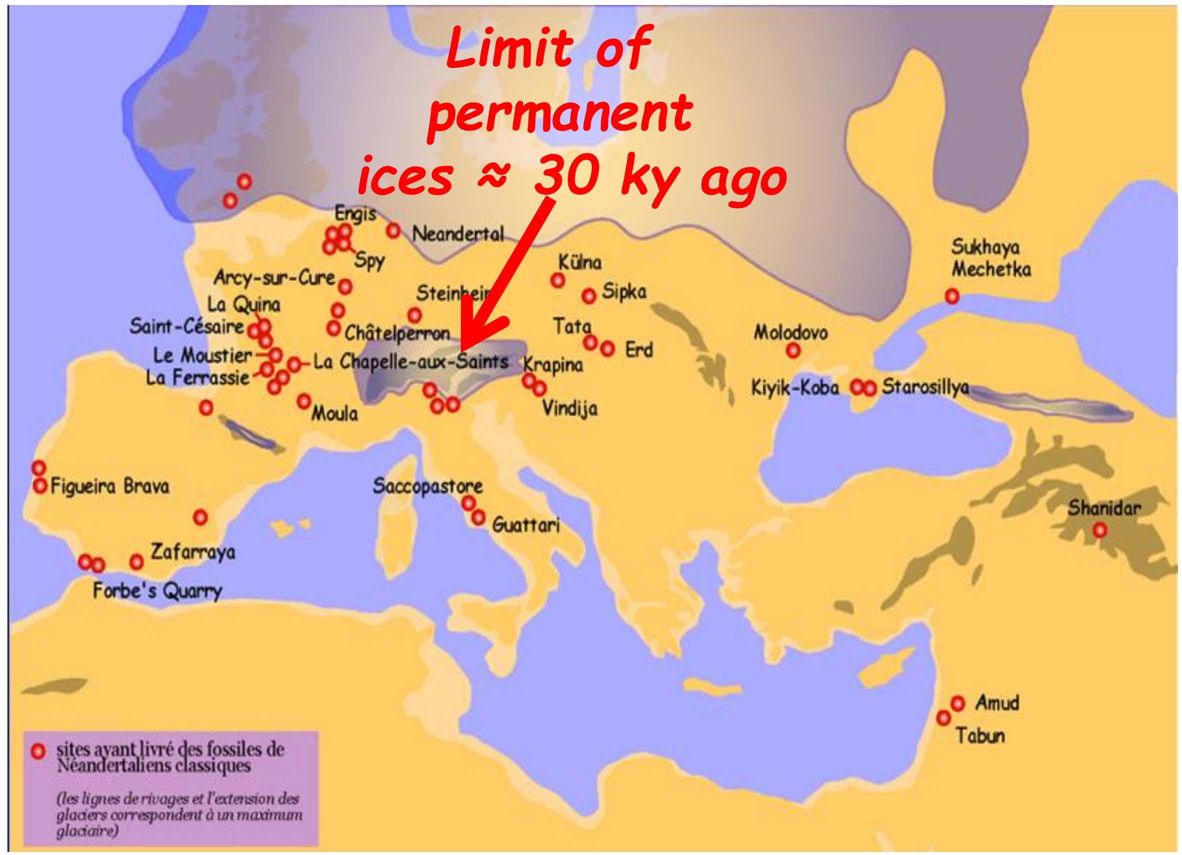
- A small African ape has been the last link between modern human apes and chimpanzees.
- The ability to walk upright developed about 4 Ma ago.
- Brain size increased rapidly, and by 2 Ma, the first animals classified as *Homo* appeared.



- Fire began with *Homo erectus* probably from 0.8 Ma to 1.5 Ma.
- Language is more difficult; it is unclear whether *Homo erectus* could speak or if that capability had not begun until *Homo sapiens*
- Modern humans (*Homo sapiens*) are believed to have originated around 200,000 years ago or earlier in Africa; the oldest fossils date back to around 160,000 years ago.
- The first humans showing signs of spirituality are Neanderthals.

Major past events:what happened to the Neanderthals ?

- Fossils have been found from northern Germany to Israel, Spain and Italy, from England and from Portugal to Uzbekistan
- It is estimated that at its peak the total Neanderthal population across this habitat range numbered around 70,000.
- Research has no accepted conclusive explanation as to what exactly caused the Neanderthal's extinction between 40.000 and 28.000 years ago.
- Hypotheses include failure to adapt to colder climate change, competitive exclusion or extinction caused by modern humans.



The colossal Campanian eruption 39,280 years ago

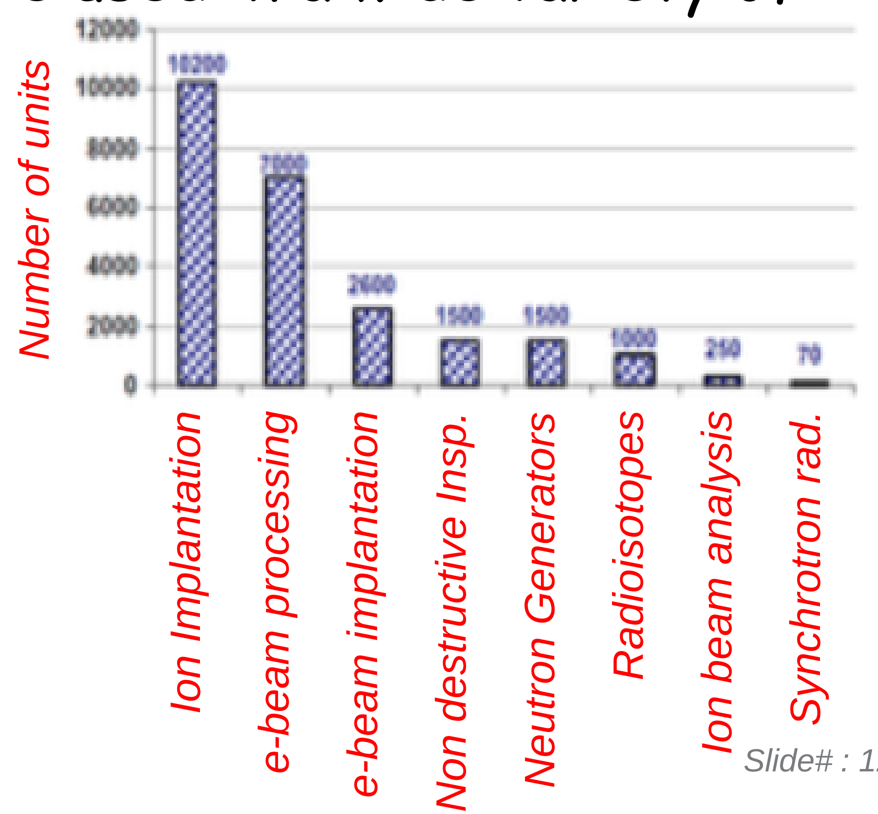
- The eruption has been classified at 7 out of 8 of Explosivity Index (VEI) with a dense rock dust emission (DRE) of> 300 km^3
- But it is unlikely to have caused the Neanderthal extinction.

DISPERSAL OF DEPOSITS DURING THE CAMPANIAN IGNIMBRITE ERUPTION AROUND 40.000 YEARS BP.

Over this area live today more than 150 million people

Presently operating accelerators

- There are currently more than 30,000 accelerators in operation around the world.
- About 1% of them are large accelerators with beams above 1 GeV used in particle physics or as synchrotron light sources for the study of condensed matter physics.
- Smaller particle accelerators are used in a wide variety of applications, including
  - radiotherapy
  - ion implantation
  - industrial processing and research and
  - biomedical and other low-energy processes



The early evolution of particle accelerators

- The history of particle accelerators had probably its origin at the Cavendish Laboratory in Cambridge around 1910.
- The interest in accelerating particles had its beginnings when *Ernest Rutherford* was astonished to observe that atoms have an incredibly small, dense mass at their centre.
- In a speech at the Royal Society in 1927, Rutherford expressed publicly the interest of the scientific community to accelerate charged particles to energies greater than those of natural α-decays in order to disintegrate nuclei with high binding energies.
- *Cockcroft and Walton* at Cavendish in 1930 were among many scientists wanting to probe experimentally the fundamental structure of nuclei. They accelerated protons to 800 keV with a multiplier consisting of capacitors and rectifying diode switchers.
- In 1928 *Van de Graaff,* then at Oxford, became interested in machines that could generate and maintain even higher voltages.

The birth of the cyclotron concept

- The cyclotron was initially conceived in Germany.
- It was proposed by Rolf Widerøe at Aachen University in 1926, who however rejected the idea as too complicated.
- In 1927, Max Steenbeck developed this concept at Siemens. The first cyclotron patent was filed by Hungarian physicist Leo Szilard in 1929, then at the Humboldt University of Berlin.
- Widerøe had then published an article in 1929: acceleration of particles might be possible with the help of a magnetic field.
- It was then one more of his ideas to use a uniform magnetic field to accelerate repeatedly particles in successive steps.
- His principle was that normal to a constant magnetic field, the frequency of rotation of a non-relativistic charged ion does not depend on the radius of the orbit. The greater distances travelled by growing orbits are exactly compensated by the increased velocity of the ions.

Original collider's patent by Wideröe, 8th Sept 1943

Erteilt auf Grund des Ersten Überleitungsgesetzes vom 8. Juli 1949
(WiGBl. S. 175)

BUNDESREPUBLIK DEUTSCHLAND

AUSGEGEBEN AM
11. MAI 1953

DEUTSCHES PATENTAMT

PATENTSCHRIFT

Nr. 876 279

KLASSE 21g GRUPPE 36

W 687 VIIIc / 21g

Dr.-Ing. Rolf Wideröe, Oslo
ist als Erfinder genannt worden

Aktiengesellschaft Brown, Boveri & Cie, Baden (Schweiz)

Anordnung zur Herbeiführung von Kernreaktionen

Patentiert im Gebiet der Bundesrepublik Deutschland vom 8. September 1943 an
Patentanmeldung bekanntgemacht am 18. September 1952
Patenterteilung bekanntgemacht am 26. März 1953

Kernreaktionen können dadurch herbeigeführt werden, daß geladene Teilchen von hoher Geschwindigkeit und Energie, in Elektronenvolt gemessen, auf die zu untersuchenden Kerne geschossen werden. Wenn die geladenen Teilchen in einen gewissen Mindestabstand von den Kernen gelangen, werden die Kernreaktionen eingeleitet. Da aber neben den zu untersuchenden Kernen noch die gesamten Elektronen der Atomhülle vorhanden sind und auch der Wirkungsquerschnitt des Kernes sehr klein ist, wird der größte Teil der geladenen Teilchen von den Hüllenelektronen abgebremst, während nur ein sehr kleiner Teil die gewünschten Kernreaktionen herbeiführt.

Erfindungsgemäß wird der Wirkungsgrad der Kernreaktionen dadurch wesentlich erhöht, daß die Reaktion in einem Vakuumgefäß (Reaktionsröhre) durchgeführt wird, in welchem die geladenen Teilchen hoher Geschwindigkeit gegen einen Strahl von den zu untersuchenden und sich entgegengesetzt bewegenden Kernen auf einer sehr langen Strecke laufen müssen. Dies kann in der Weise durchgeführt werden, daß die geladenen Teilchen zum mehrmaligen Umlauf in einer Kreisröhre gezwungen werden, wobei die zu untersuchenden Kerne auf derselben Kreisbahn, aber in entgegengesetzter Richtung umlaufen. Da die geladenen Teilchen dabei nicht von bei der Reaktion unwirksamen Elektronen abgebremst werden und andererseits auf einer sehr langen Wegstrecke gegen die Kerne sich bewegen können, wird die Wahrscheinlichkeit für das Eintreten der Kernreaktionen wesentlich größer und der Wirkungsgrad der Reaktion sehr stark erhöht.

Um die bei der Kreisbewegung entstehenden Zentrifugalkräfte aufzuheben, müssen die umlaufenden Teilchen von nach innen gerichteten Ablenkkräften gesteuert werden, während eine Diffusion der Teile mittels stabilisierender, von allen Seiten auf den Bahnkreis gerichteter Kräfte verhindert wird. Falls die gegen-

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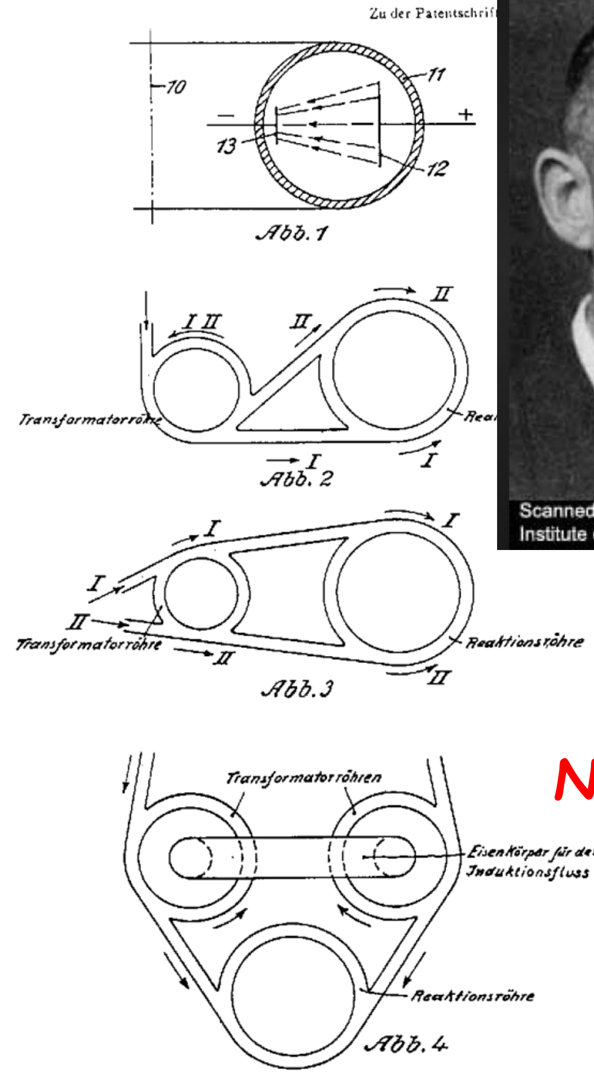
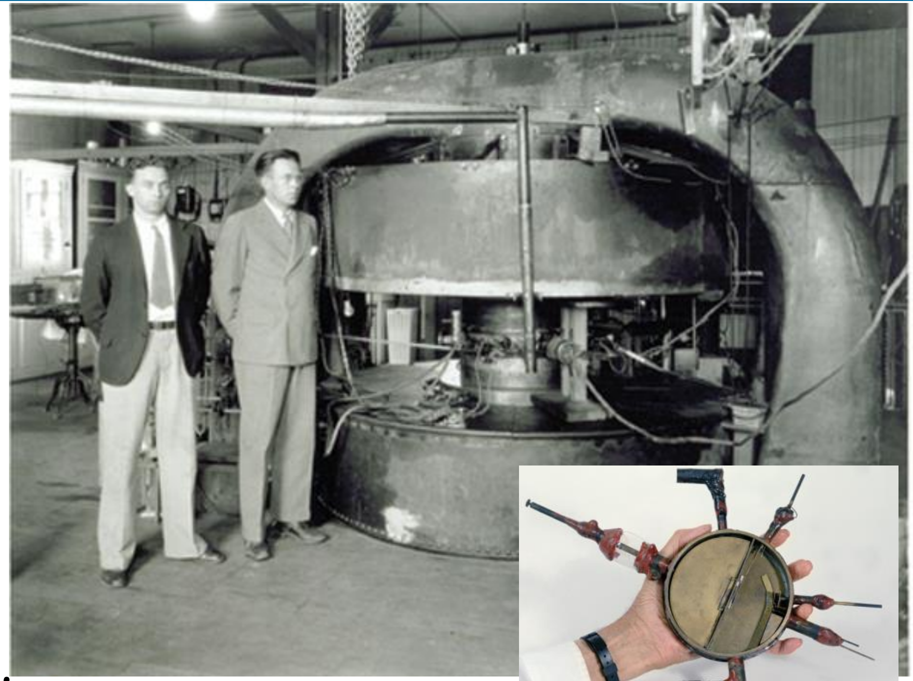


Wideröe, a missed Nobel prize ?

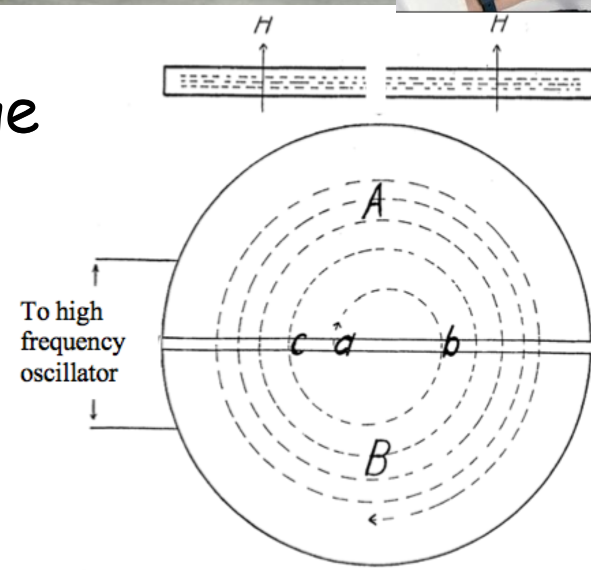
During rough war times, a patent was the only way to communicate the notion ! but not published until 1952.

The practical realization of the cyclotron

- Ernest Lawrence of the University of California, Berkeley had read the original article in German by Rolf Widerøe.
- A first 4" cyclotron was then actually constructed by Lawrence and operated in 1932. with his graduate student, M. S. Livingston.



- **A** and **B** are hollow metal half-cylinders alternately charged to a ≈ 1000 V voltage by an oscillator at 10 MHz.
- At the correct frequency, the alternating voltage would be resonant with the angular rotation related to the value of the magnetic field rotation.



The introduction of the "strong focussing"

- Until 1952, focusing in the transverse plane had a constant gradient with a very small tolerance and a large beam aperture.
- In 1952, Courant, Livingston, and Snyder at BNL proposed a new type of transverse focusing, which they called strong, or *alternating-gradient (AG) focusing*.
- Depending on the size of the uniform gradient across the magnetic aperture of individual magnets, particles passing through such a field will be either focused or defocused.
- Focusing in one transverse plane will be defocusing in the other plane. With a chain of focusing, defocusing and field-free magnetic sectors of equal focal strength, the combined focal length will be positive and the beam will converge in both planes.
- The principle of AG focusing completely changed the basic design for magnets used in synchrotrons. *Magnets and vacuum chambers could be made far smaller— with huge savings in cost and size*.

The beginning of CERN physics

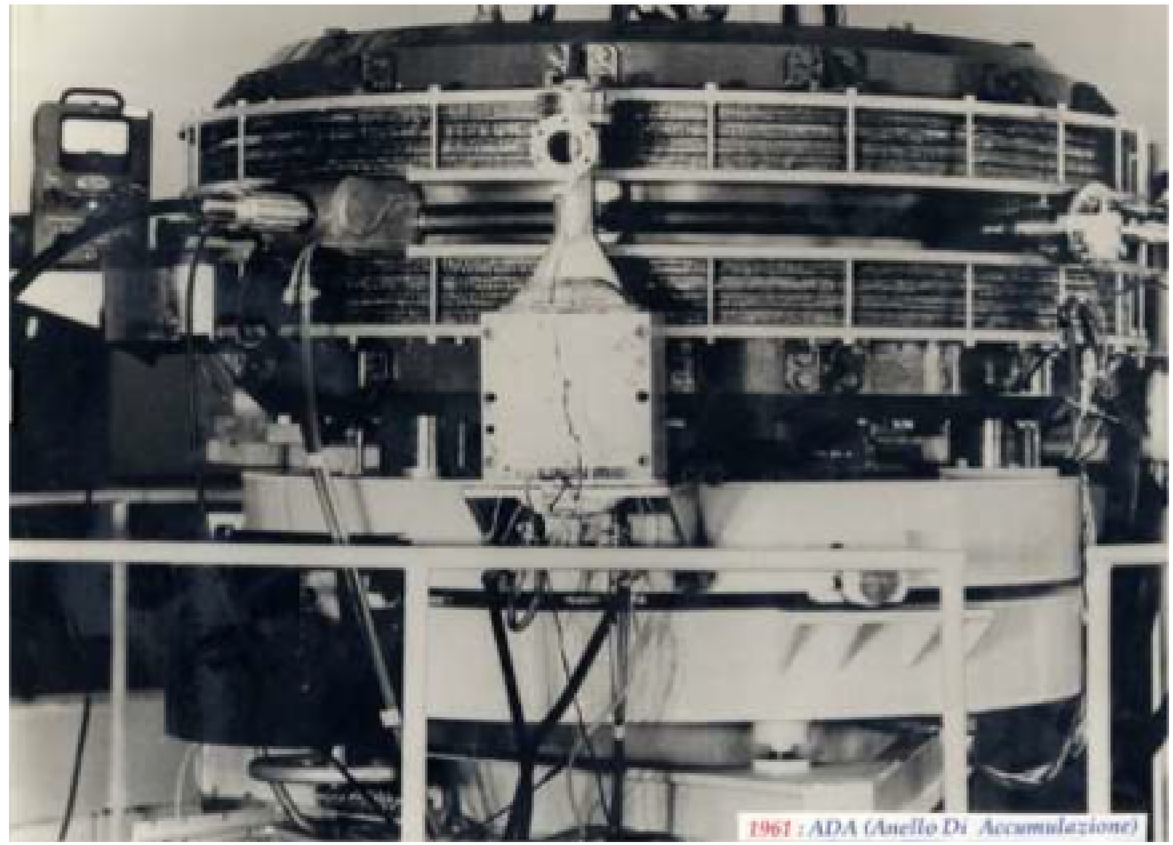
- This new development at BNL had a nearly instantaneous effect. A young and brilliant British physicist, John Adams initiated the conversion into an AG Synchrotron at CERN in 1955.
- In 1959, the CERN Proton Synchrotron (CPS) was brought online, eventually reaching 28 GeV, later followed in 1960 by the Brookhaven Alternating-Gradient Synchrotron (AGS 33 GeV)
- The first electron but smaller AG synchrotron was finished in the US by R.R. Wilson at Cornell University and operated at 1 GeV.
- US Researchers with AG synchrotrons received 3 Nobel prizes in physics for the discovery of the J/psi particle in 1976, the CP violation in 1980 and for the discovery of muon-neutrino in 1988
- G 't Hooft and J. G. Veltman from Holland received the Nobel in 1999 showing the way to renormalize the "electro-weak" theory,

The first electron positron collider

- For a stationary target and a beam of energy E>> mc^2 ; $E_{cm} \approx (2Emc^2)^{1/2}$.
- In the more effective colliding beams set-up, with two accelerated beams, each of energy E, directed against each other, we have $E_{cm} = 2E$
- Gain ratio $[(2E)/(mc^2)]^{1/2}$
- The first colliding e+-e- were built in the early 1960s: ADA in Frascati near Rome and VEP-1 in Novosibirsk (USSR)

ADA (*Anello Di Accumulazione*) at INFN, Frascati, Italy

– 250 MeV e^+ x 250 MeV e^-

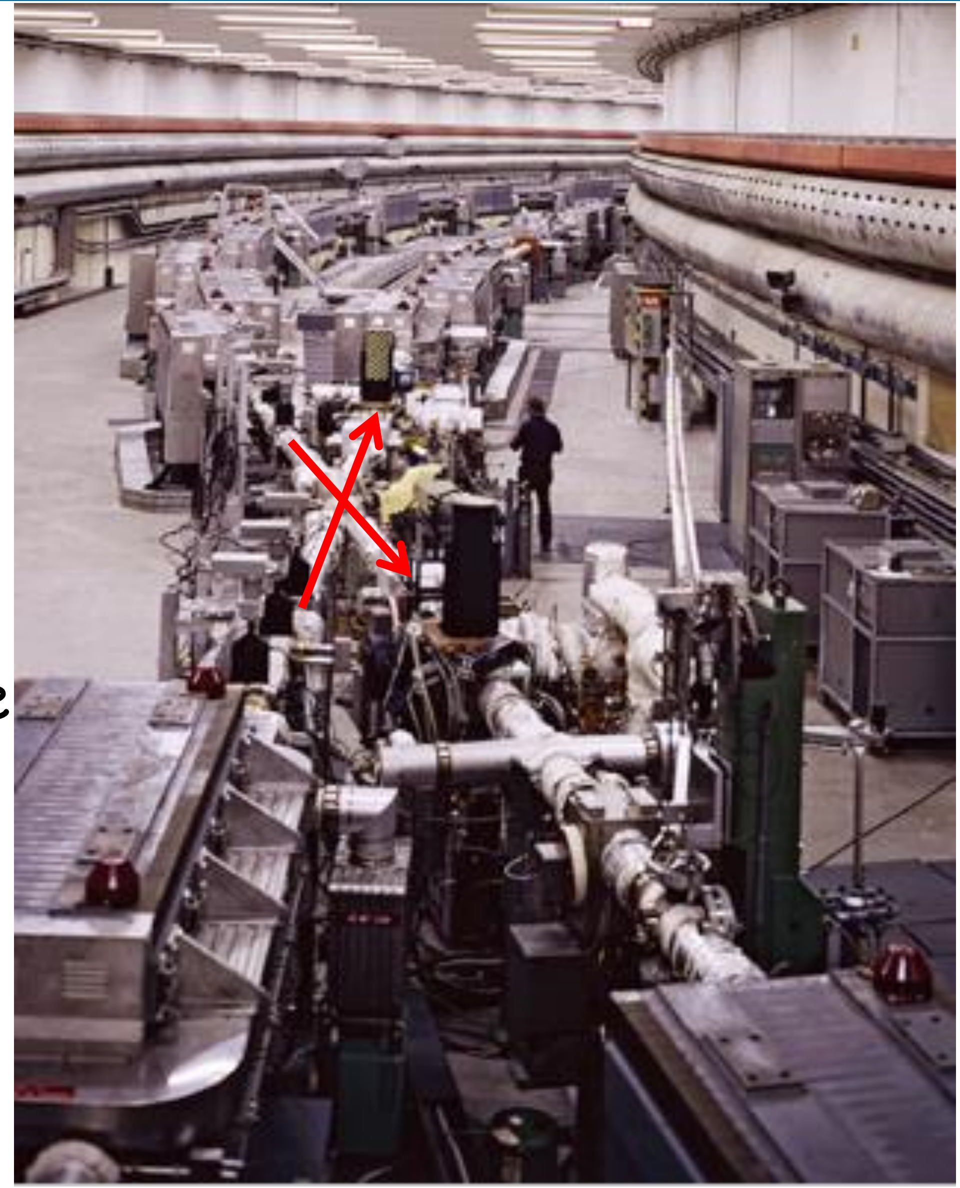


– 1961 : Construction Finished

– ~ May-June 1964: Luminosity Detected

The first hadron (proton-proton) collider

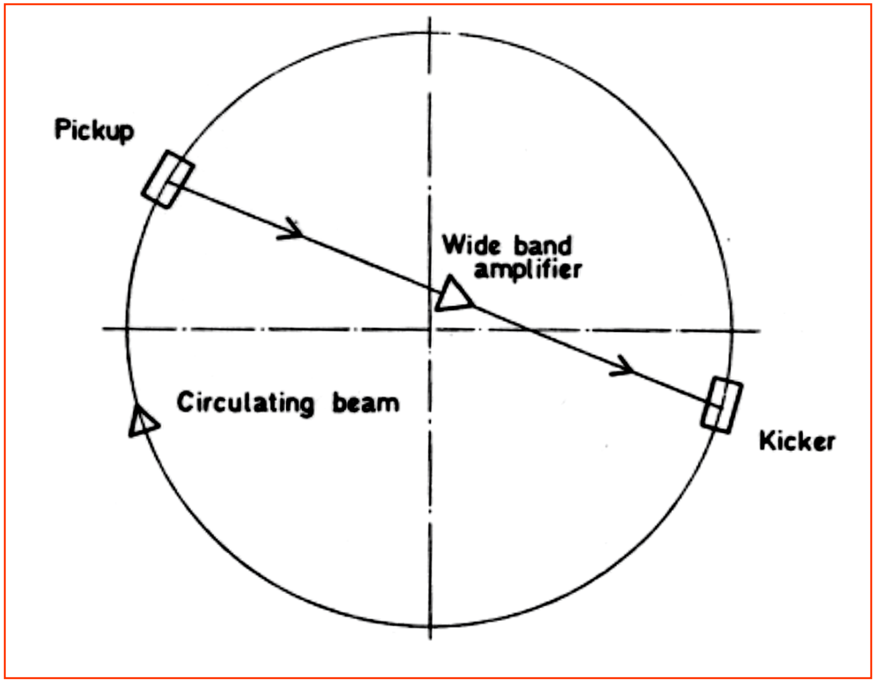
- Construction of the first hadron (proton-proton) collider, called *Intersecting Storage Rings*, began at CERN (Switzerland) in 1966. The collider was operational in 1971.
- The radius of the ring was 150 m with 8 crossing points of the two counter-rotating proton beams at an angle of 15 deg. Its highest c. of m. energy has been 63 GeV.
- A stack of a DC current of up to 50 A has been stored from protons from the CERN-PS.

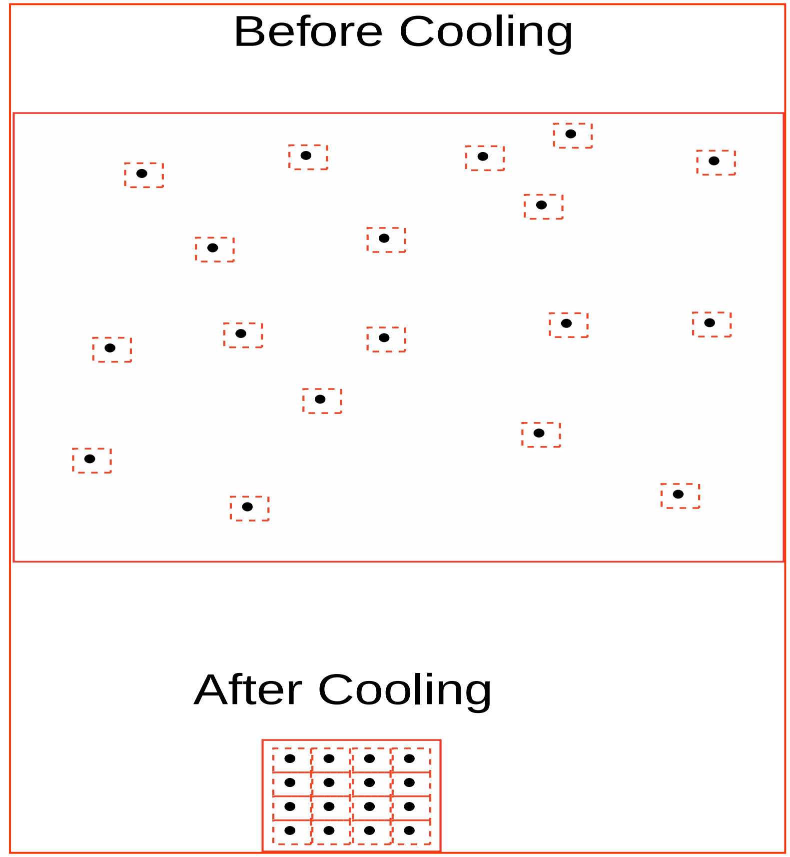


Antiproton Accumulator (AA) and Antiproton Collector (AC)

A very clever method: the stochastic cooling

- *Stochastic cooling* (Van Der Meer) is taking advantage of the fluctuations inherent in a finite number of particles.

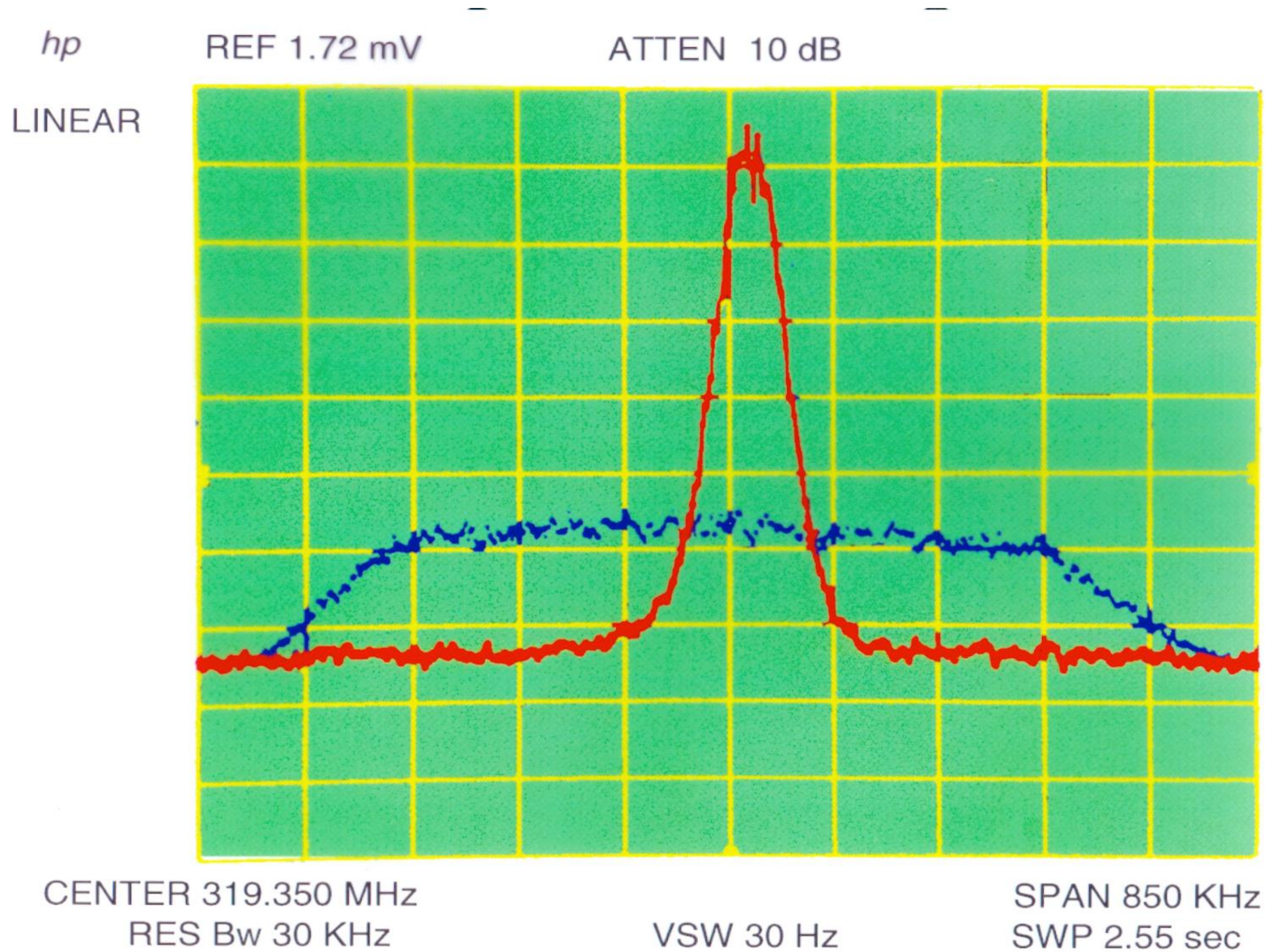




At each passage, the "kicker" corrects the average value of the fluctuations as measured by the "pick-up" to zero.

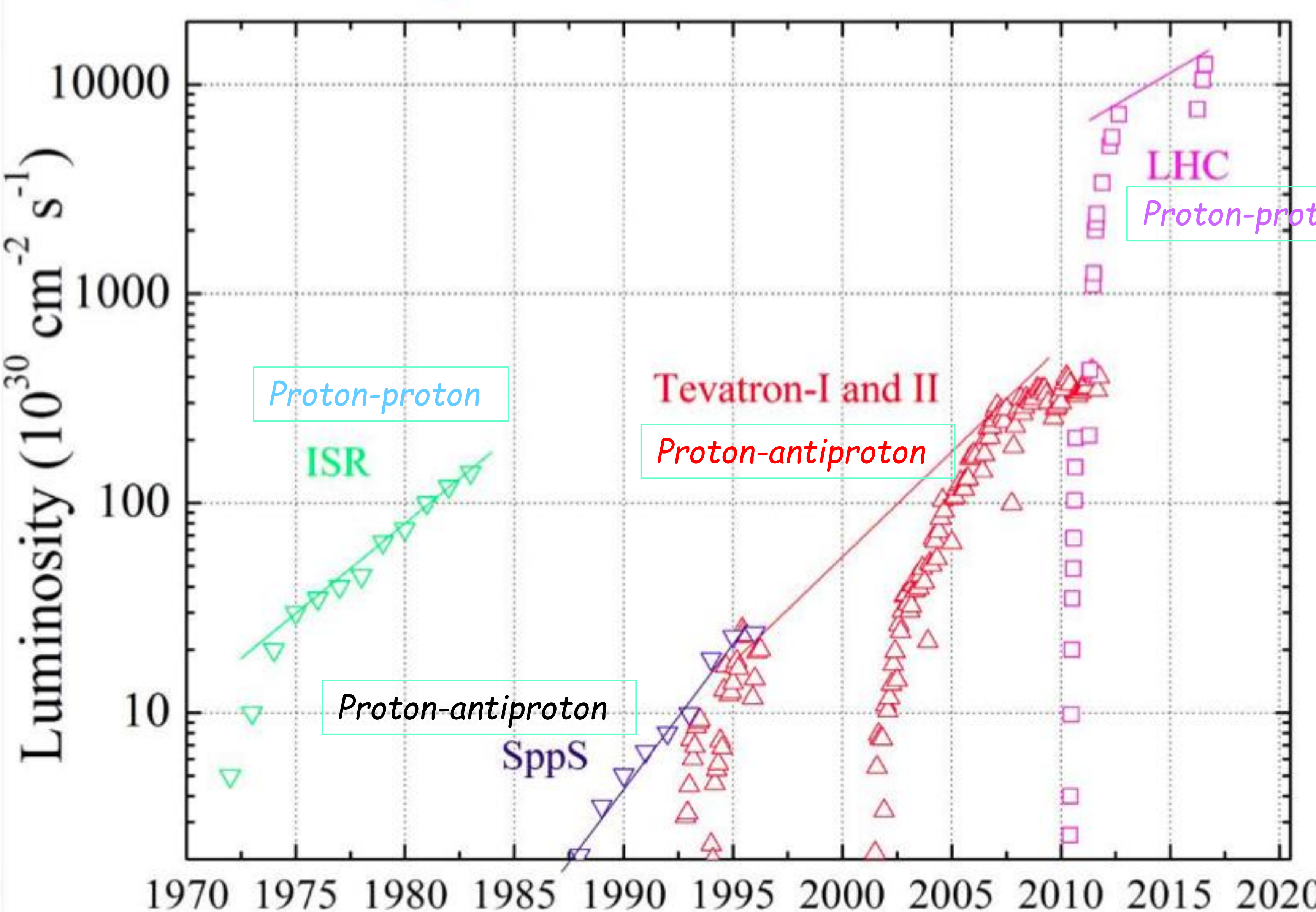
The points which contain a particle are individually pushed closely together.
Liouville's theorem is fulfilled !

Antiproton cooling in 2 sec !

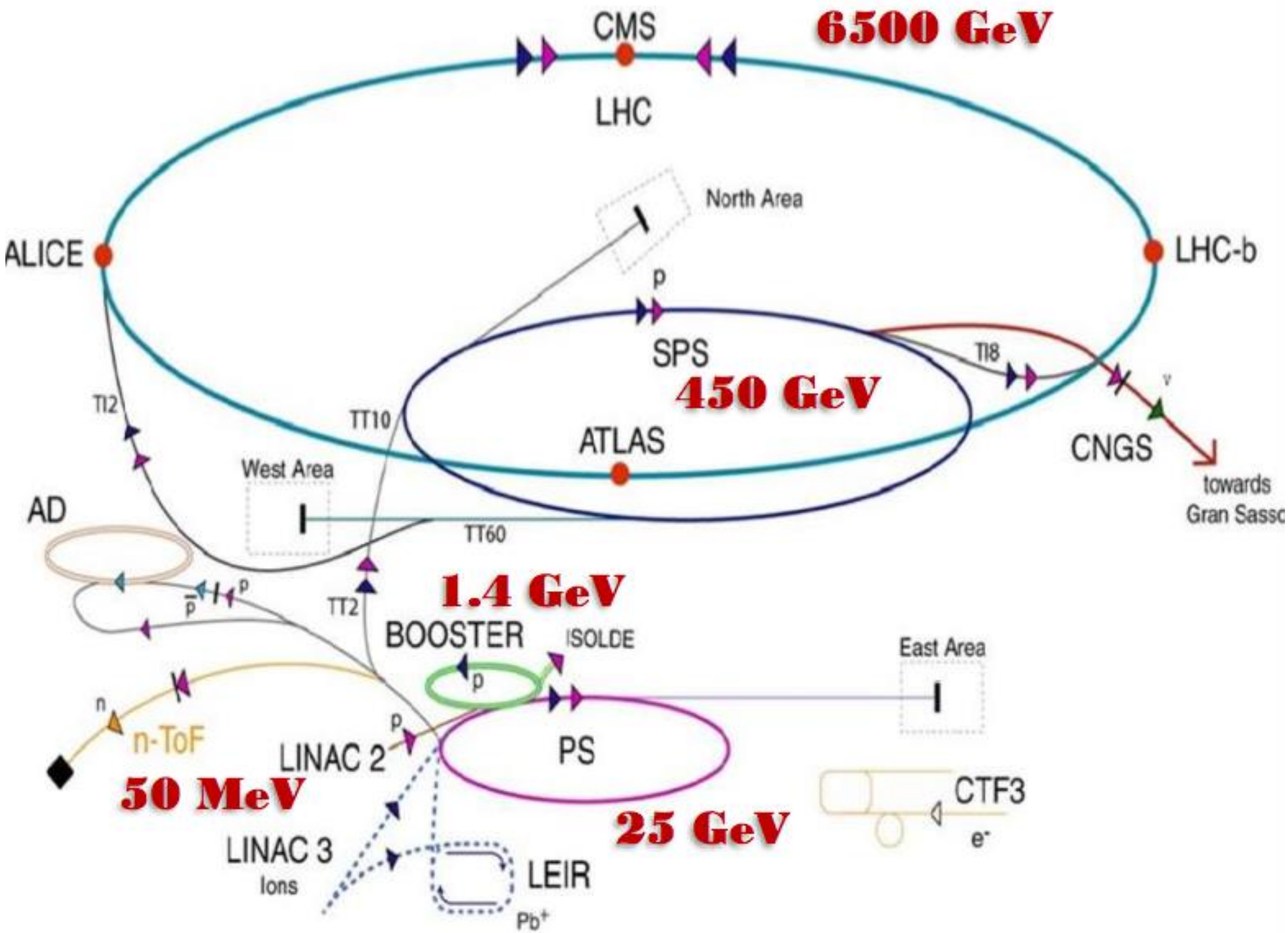


Precooling 6 x 10^6 $\bar{p}$'s in 2 seconds. Longitudinal Schottky band at the 170th harmonic (314 MHz) before and after cooling.

Luminosity evolution of P-P and Pbar-P colliders



CERN Accelerator Complex in 2016

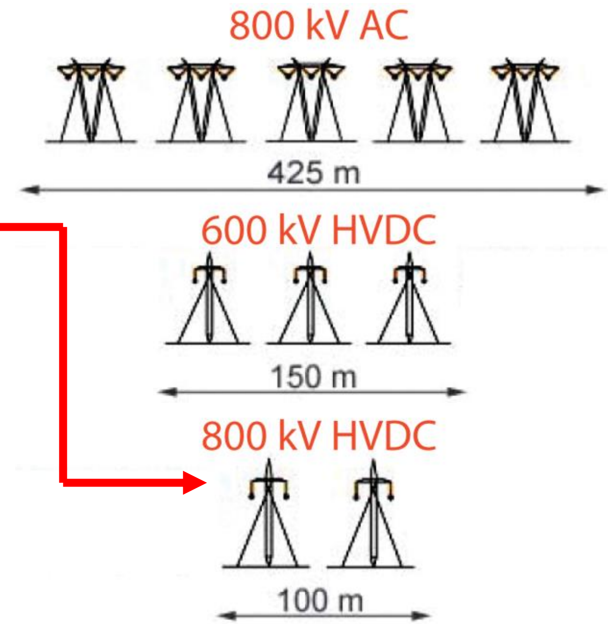


The tunnel of LHC

The huge dimensions of LHC are evident from its tiny curvature

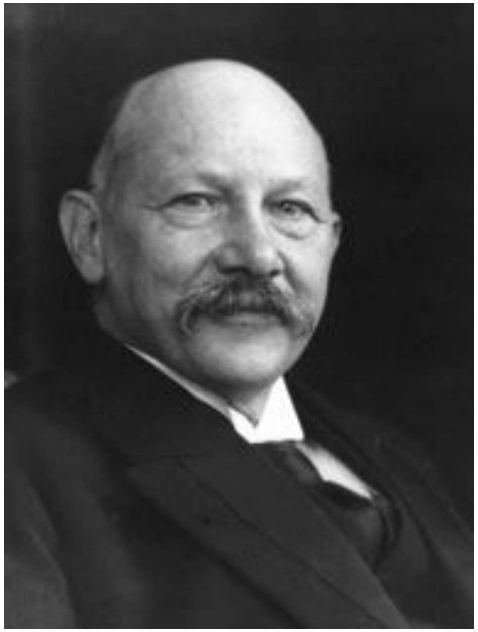
Ordinary high power overhead lines for long distances

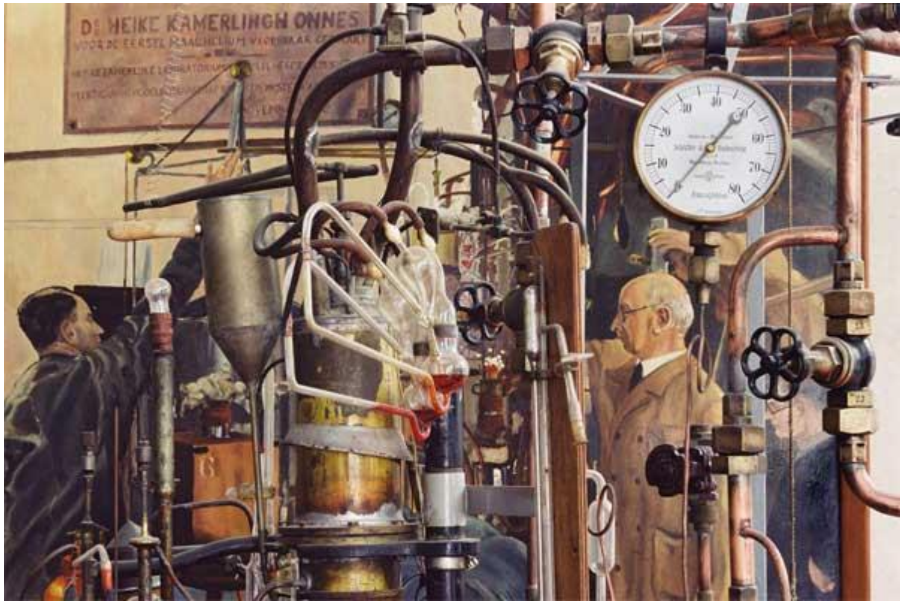
- Overhead NC lines can be constructed safely, but tall, massive and unsightly.
- The typical capital investment for 10 Gwatt, ± 800 kV and 3600 km is 5 G€, and ohmic losses are about 0.5 G €/y
- A project from Sahara to EU for 10 GW requires 225 km^2 of Solar, but as much as 360 km^2 of overhead lines !



- DC mode is mandatory because of cable added capacitances.
- In submarine or congested areas sections, cables are needed.
- Heating and ohmic losses limit each cable to about 1 GW.
- Cable costs are much larger, ≈ 5-10 times overhead lines.
- Insulations are made with oil impregnated paper, poly-propylene: a lower practical voltage (± 500 kV) ?

100 years of Super-conductivity

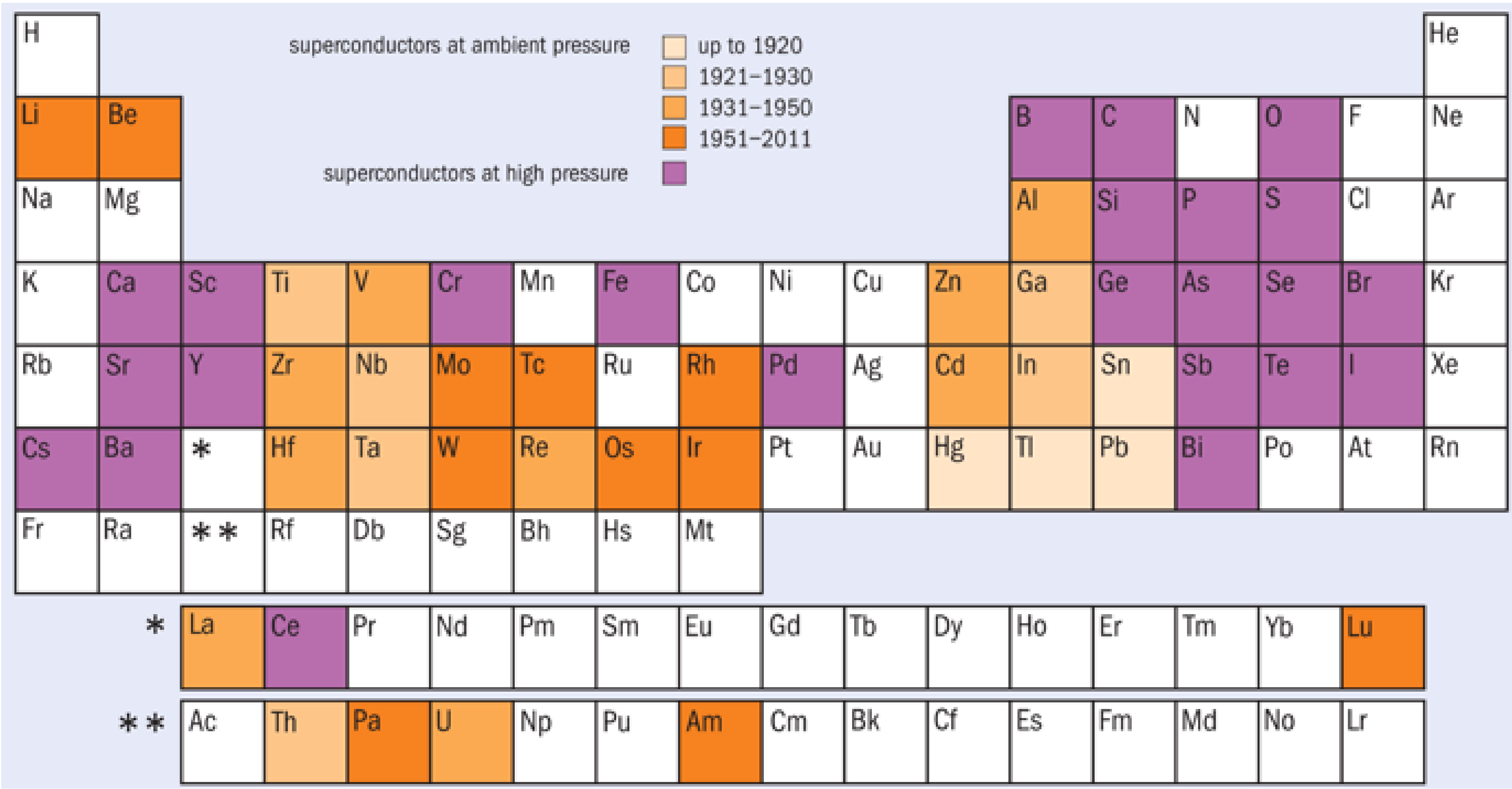




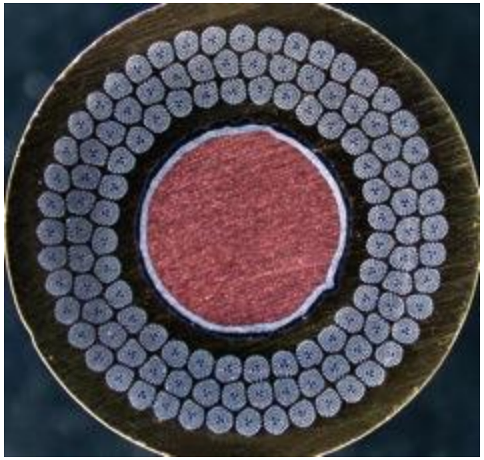
- The absolutely perfect conductivity (zero resistivity) was discovered by Heike Kamerlingh-Onnes together with Gilles Holst in 1911. This was made possible by the liquefaction of He at 4.3 K (-269° C) in 1908.
- Interestingly, Kamerlingh-Onnes proposed already in 1915 that a persistent current loop be built between Paris and London.

Superconductivity: spreading its wings

- Over the last 100 years, an ever bigger range of elements in the periodic table has been found to superconduct, either at ambient pressure (yellow/orange) or at high pressure (purple)

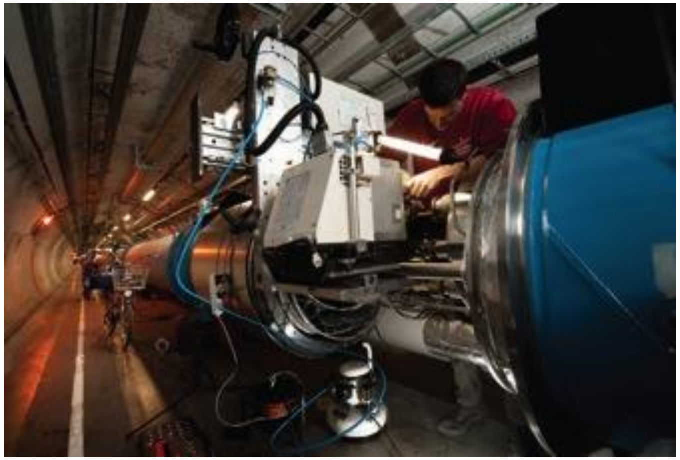


Five top applications of superconductivity

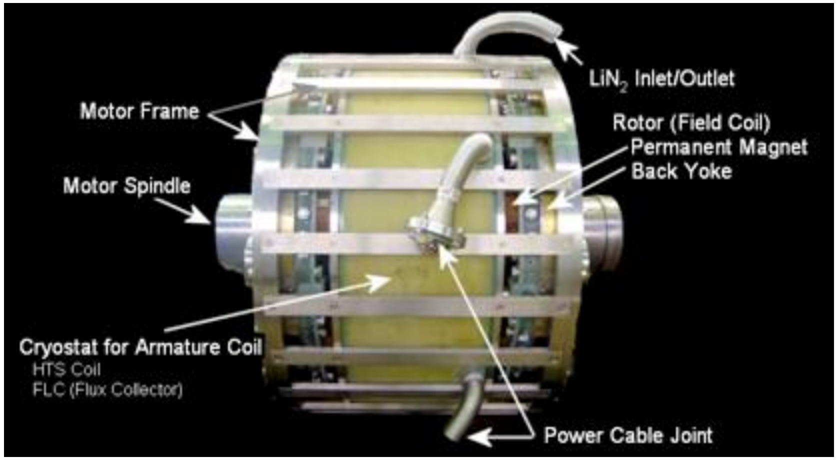


1. Wires and films

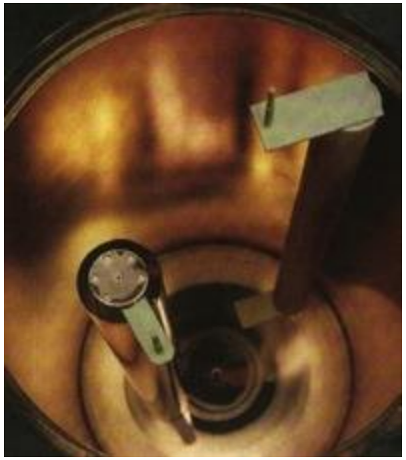
2. Medical imaging



3. High-energy physics



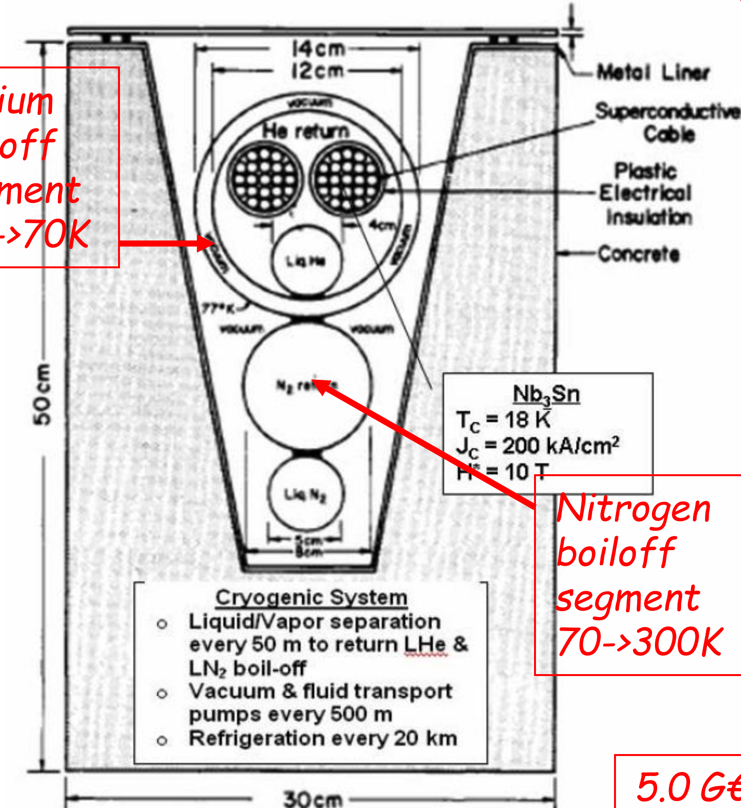
4. Rotating machinery



5. Dark matter

The first steps with superconductivity

- Richard Garwin and Juri Matisoo laid in 1966 the foundations of the *Superconductive Alternative for very long distances.*
- The G+M proposal was based on the bold assumption of 100 GWatt DC and 1000 km (then about ½ of the electric US power) contained *inside a box of 30 x 50 cm² cross section* !



ABSTRACTED TABLE I FROM GARWIN-MATISOO [1], COMPARING VARIOUS COMPONENT COSTS OF A 1000 KM, NB-SN CABLE IN 1966 AND NOW

Item	Description/Quantity	1966 Cost (M$)	2006 Cost (M$)*
Superconductor	10^4 Tons Nb_3Sn	550	3405
Line Refrigeration	0.5 M$ for 1 kW LHe station every 20 km	25	155
End-Station Refrigeration	10 kW each	5	31
Vacuum Pumps	$500 per station (2000)	1	6
Fabricated Metal	$1/lb, linear line weight = 100 gm/cm	20	124
Concrete	$10/yd³ for a total volume of 0.5 yd² times 1000 km	5	31
ac/dc Converters	Thyristors at $1/kW	200	1238
Total:		806	4990

*2006 costs relative to 1966 are estimated from the Bureau of Labor Statistics table of annual Consumer Price Indices that can be found at ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt. The 2006/1966 ratio used above is 6.19

P. M. Grant

5.0 G€ for 1000 km and 100 GW, dominated by the cost of SC (69%)

A cryogenic system over thousands of km ?

- The original G.+M. method was based on He boiling at 4.2K:
  - continuous separation of liquid to vapour every 50 m
  - a very frequent (every 500 m) vacuum and circulating pumps
  - A main refrigeration station every 20 km.
  - Additional, double phase N_2 coolant from 70 to 300 K

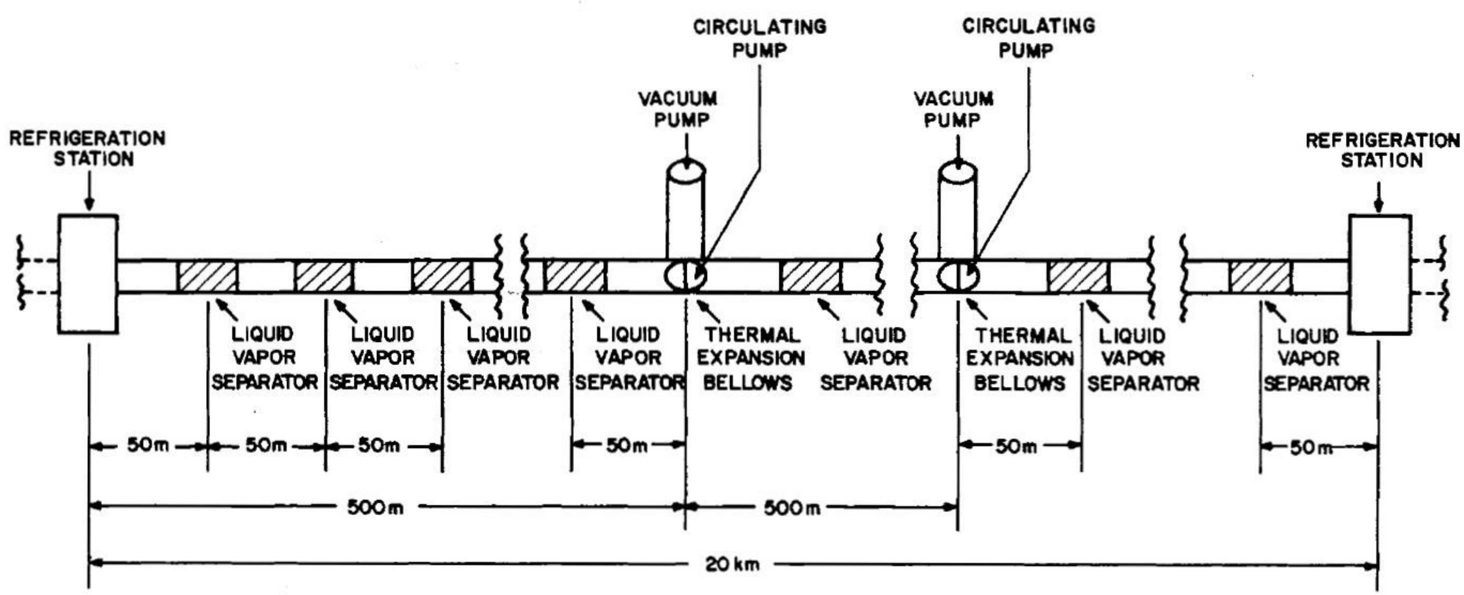


Fig. 2. A 20-km module of the 1000-km, 100-GW line.

Too complicated to be competitive

- H_2 and/or N_2, He gas and higher temperatures SC may offer much simpler systems based on single phase, liquid coolants.

The discovery of new superconducting materials

- In 1986, the biggest breakthrough has been the discovery of Cuprate High Temperature Superconductors (HTS), by *Nobel Laureates Bednorz and Müller.*
- Because of their critical temperature, well above that of the cheap and readily available liquid nitrogen coolant, these new materials have changed for ever the impact of SC.
- In January 2001, the community has been again astonished by the sudden announcement of *Akimitsu et al.*, reporting superconductivity at 40 K by MgB_2, or Magnesium Diboride.
- This surprisingly simple and cheap compound can be readily manufactured into wires, and is based on precursors that are very abundant and cheaper than any other competing SC.
- MgB_2 is a logical step of evolution for most applications and while waiting for the Cuprate HTS to reach their targets.

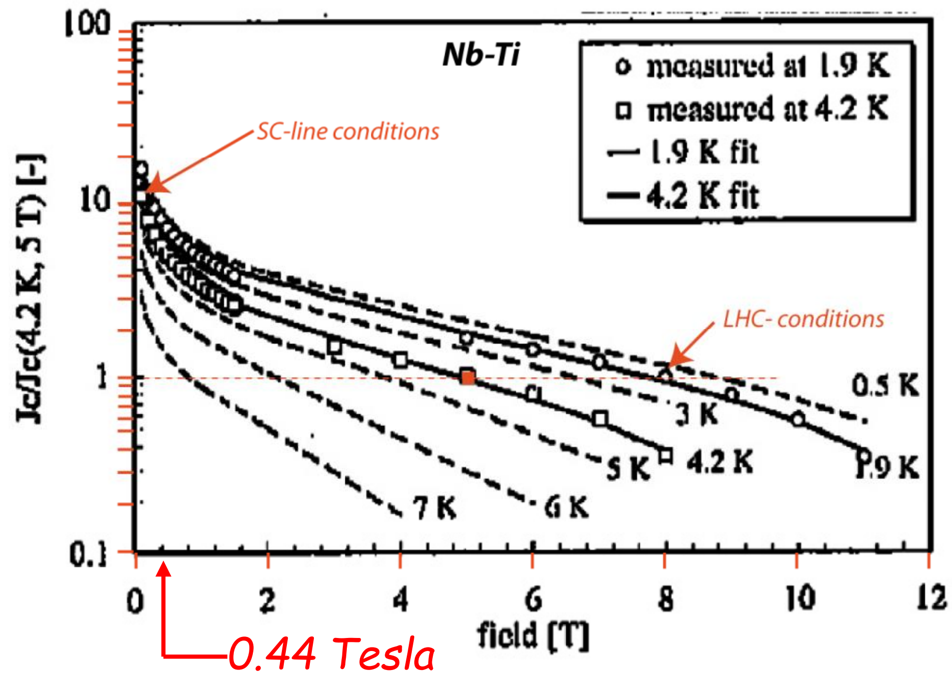
Choices of the SC alternatives

- Existing superconducting materials and cryogenic components do not deliver a competitive alternative to the existing technology.
- Both recent progress and ongoing research promise to improve performance and reduce costs so that a competitive parity with conventional transmission is expected in a few years' time.
- *The relatively recent development of MgB_2 superconductor appears as the most desirable solution which may provide a low cost cable and a sufficiently high cryogenic temperature.*

SC Material	*Main Coolant*	*T (K)*	*Thermod factor*	*Cable wire costs*	*kryogenic-complexity*	*cable complexity*
NbTi	liquid He	1.9-4.3	400	low (≈1 kA m)	high	low
HTS	liquid N_2	60-75	9	high (>50 kA m)	low	high
MgB_2	liquid H_2 or gasHe+LN_2	15-20	40	low (<1 kA m)	low	low

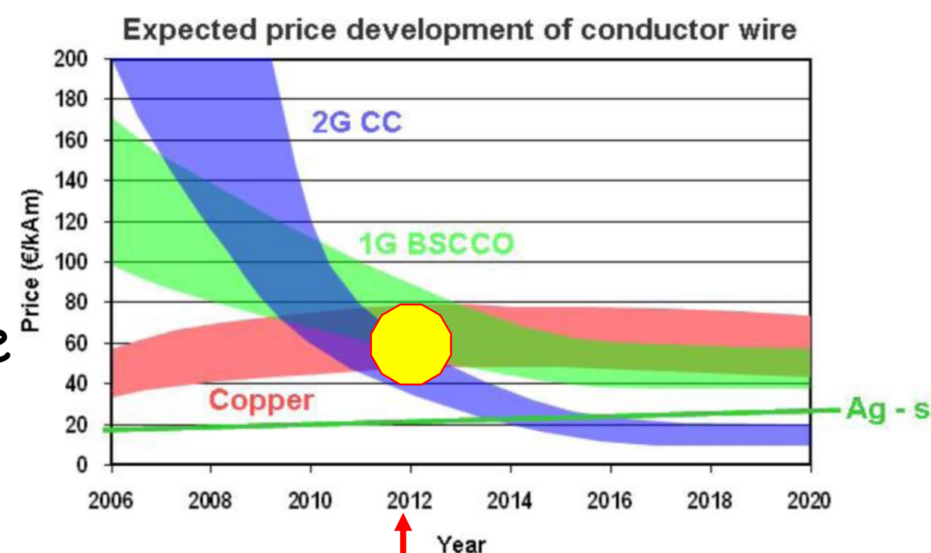
1.-Traditional Nb-Ti superconductors at liquid He temperature

- NbTi is the most used SC, in our case with Cu stabilization.
- Let us assume a realistic 10 GWatt transported over 3600 km and HV's = ±250 kV, corresponding to a current J = 20 kA.
- The LHC as a reference has produced 7000 km of wire with 50 kA J_c field at 8.3Tesla, about the annual world production.
- However for this application the magnetic field B_{max} is now very small ≈ 0.44T (4400 G)
- For a conductor length of 2 x 3600 km, Jc ≈ 50 kA and T = 4.2 K only about 10% of the LHC-SC stockpile is necessary
- The total cost of the NbTi wire at B = 0.44 T is quite modest, ≈ 0.2 €/(kA m), namely 72 M€ (!).



2.- HTSC alternatives: high costs and complexity

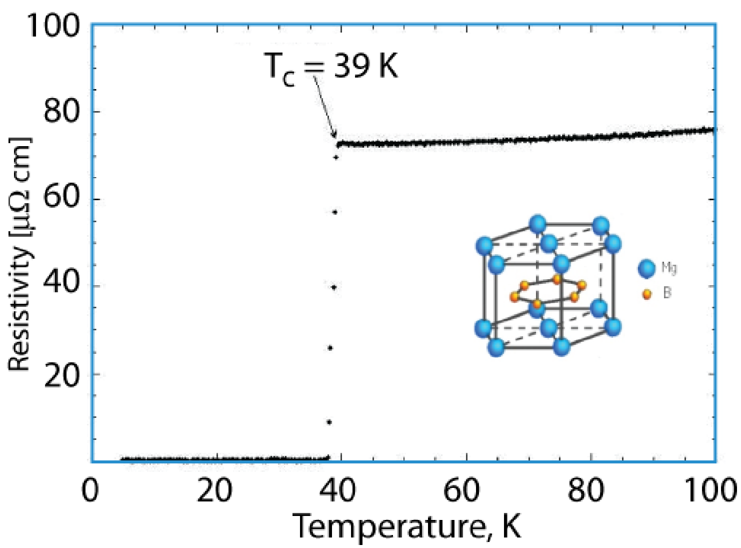
- Both solutions, Bi-2223 (1G) and Y-123 (2G) look possible and have similar current characteristics and temperature range.
- In view of the potential for cost reduction more work is being put into developing Y-123 in form of coated conductor, so this material is now preferred for new cable studies.
- The high cost of the superconductor is a limitation. Bi-2223 is today > 100-200 times more expensive than Nb-Ti
  - Cable properties are of concern since they have a considerable mass and need to withstand big forces during handling.
  - There are hopes that future price may be reduced: however for the moment the cost and complexity are the most serious problems.



As a comparison, the cost of Nb-Ti is ≈ 0.2 € kAm

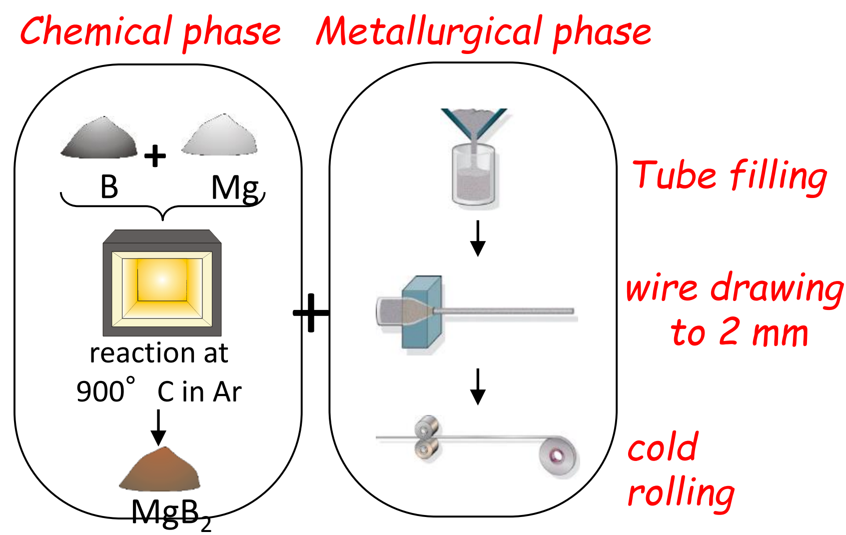
3.- The new choice in long power lines: MgB_2

- In January 2001 superconductivity was announced for a simple new compound, the Magnesium Diboride, MgB_2.
- MgB_2 is under development and relatively small quantities of cable have been manufactured so far at the laboratory scale.



Manufacturing of MgB_2 wires

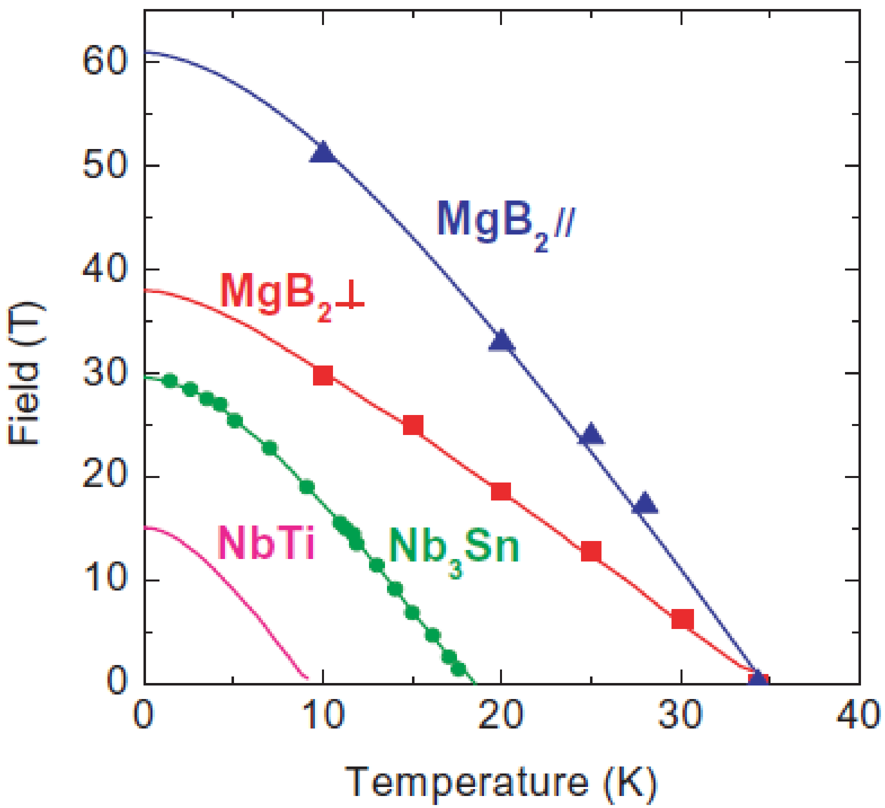
by simple *ex-situ* Powder-In-Tube method



- An extremely simple method of producing the cheap chemicals and of drawing the wire, in analogy with Nb-Ti.
- Wire unit length today up to 4 Km in a single piece, easily scalable by increasing billet size/length.
- Conductor cost at 20K, 1T:now 1.5 €/kAm; in 3 y 0.5 €/kAm

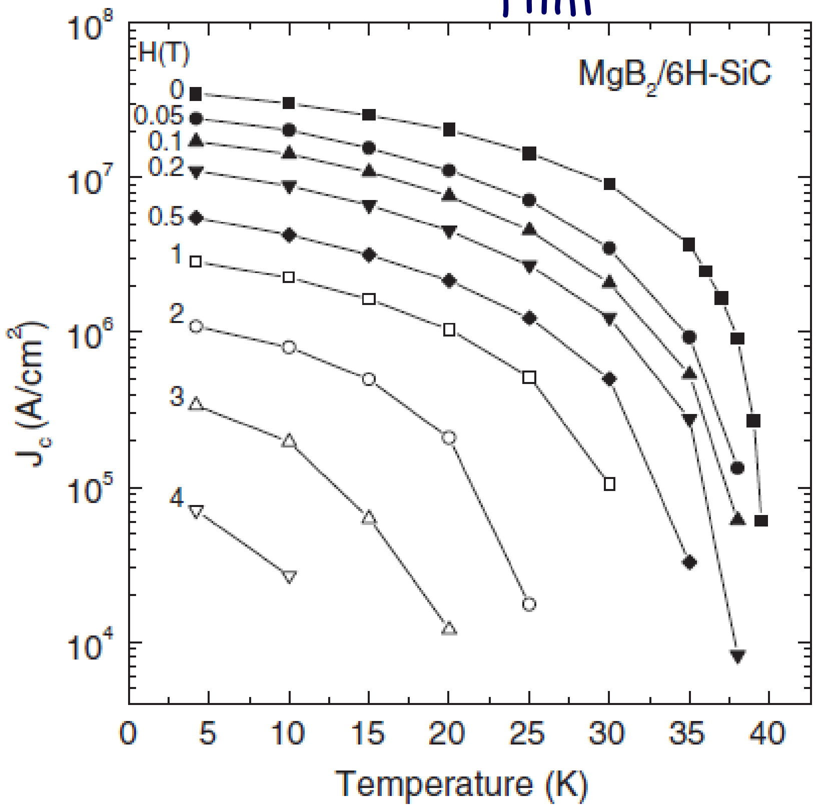
Why MgB_2? Promising features

High critical field in thin film



Iwasa Y et al. 2006
A round table discussion on MgB2:
towards a wide market or a niche production?
IEEE Trans. Appl. Supercond 16 1457-64

Large critical current density on thin film



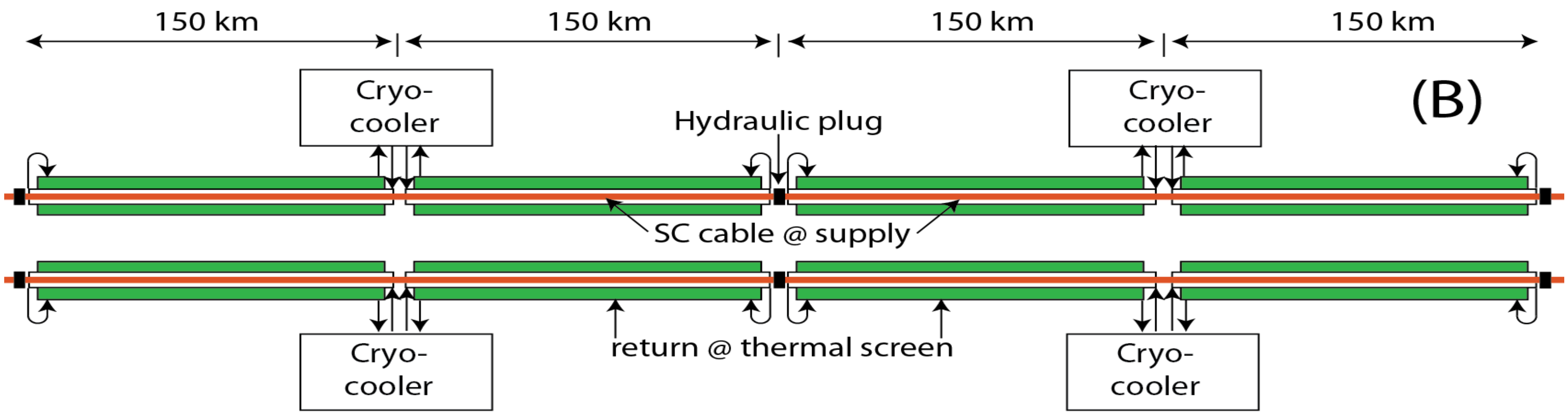
Zeng et al. 2003
Superconducting MgB2 thin film
on silicon carbide substrate by HPCVD
APL 82 2097-9

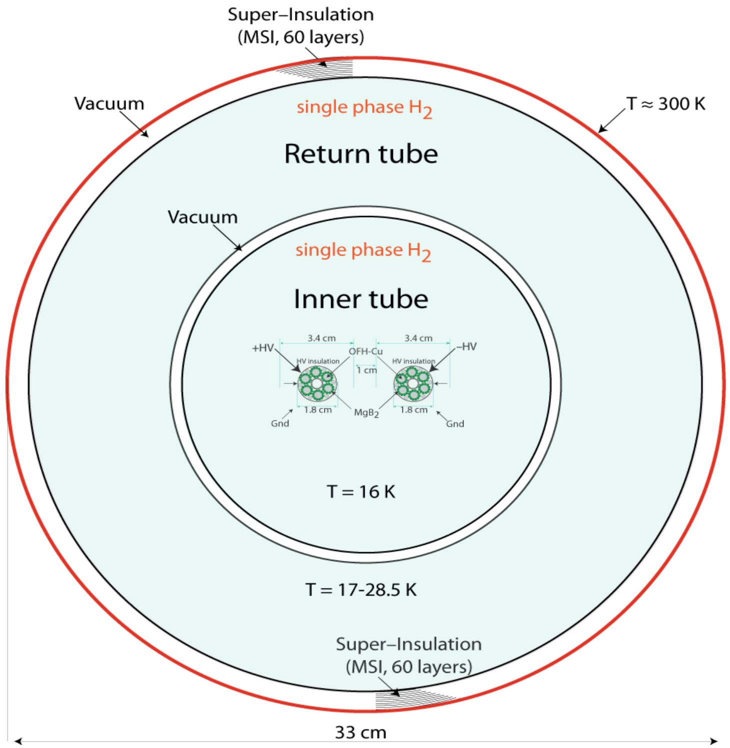
Relative merits of a MgB_2 based high power DC line

- Cu stabilized wire and easy production demonstrated with abundant and cheap materials (B and Mg of reasonable purities)
- Low cost of SC wire, projected in 3 years to about 0.5 €/kAm.
- Conductors for 2x3600 km and J_c= 86 kA (I = 20 kA, 10 GWatt), 300 M€, about a factor 100 cheaper than today's HTSC.
- Single phase liquid H_2 cooling with modest additional cryo-cooling with respect to N_2/ HTSC. Electric power: 4 MW/3600 km.
- Transmission peak powers of 10-20 GWatt HVDC are possible, still dominated by cryogenic losses.
- Very long segments of several hundred kms offer small diameter, pressure losses and remarkably simple geometries.
- A test prototype of considerable lengths (many km) and power (GWatt's) can be promptly realized.
- Low density of H_2 permits wide altitude differences along the pipeline (δp = 6.7 bar for δz = 1 km)

Cooling and electric concept for MgB_2 Transmission Line

I = 20 kA
V = ±125 kV





A comparison: Natural Gas pipeline for the same but thermal energy
90 cm diameter
Pressure 100 bar
Cryo-cooler every 300 km

33 cm diameter
Pressure 20 bar

Efficiency for various options

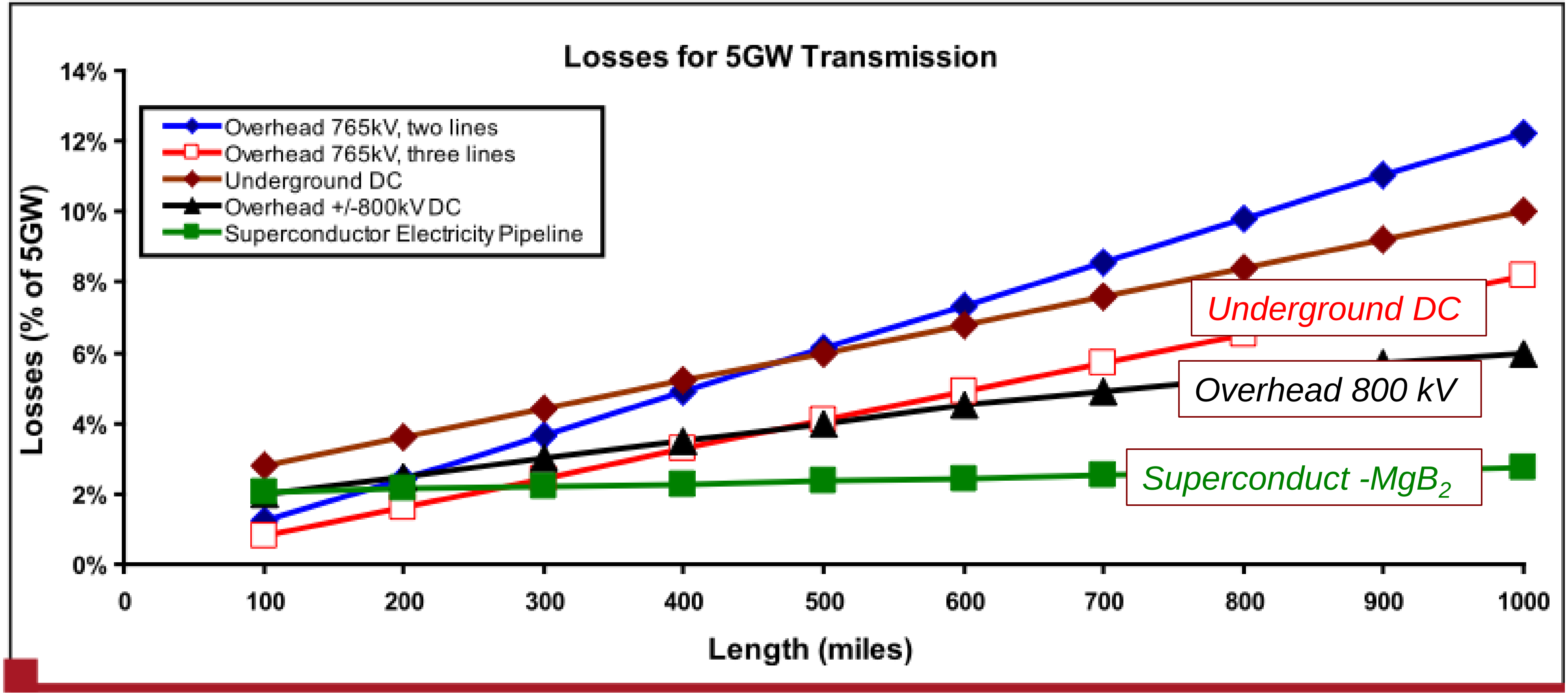
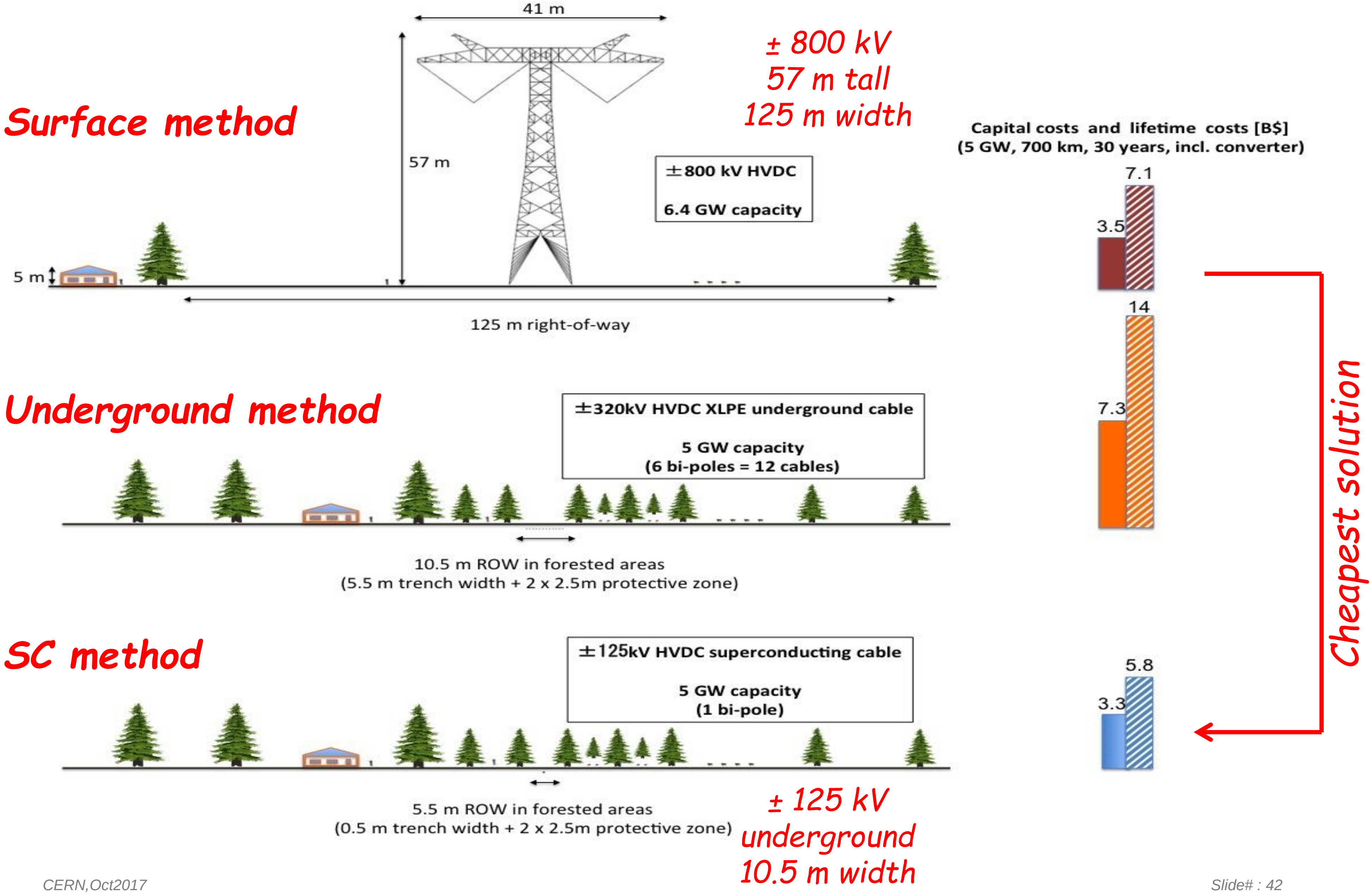


Figure 9: Efficiency of various transmission options.

Cost comparison for 700 km length and 5 GW capacity



Major related discoveries with particle accelerators

- At SLAC: Stanford Linear Accelerator Center, in California, where the *charm quark* (also discovered at Brookhaven) and tau lepton were discovered.
- At BNL: Brookhaven National Lab, in New York, where simultaneously with SLAC the charm quark was co-discovered
- At Fermilab: Fermi National Laboratory Accelerator where the *bottom and top quarks* and the *tau neutrino* were discovered.
- At CERN: European Laboratory for Particle Physics, crossing the Swiss-French border, where *the W and Z particles* were discovered.
- At DESY: Deutsches Elektronen-Synchrotron, in Hamburg, Germany where *gluons* were discovered
- At CERN: CMS and Atlas have observed a narrow line of high significance at about 125 GeV mass, compatible with the *Higgs boson*.

The many other applications of accelerators.

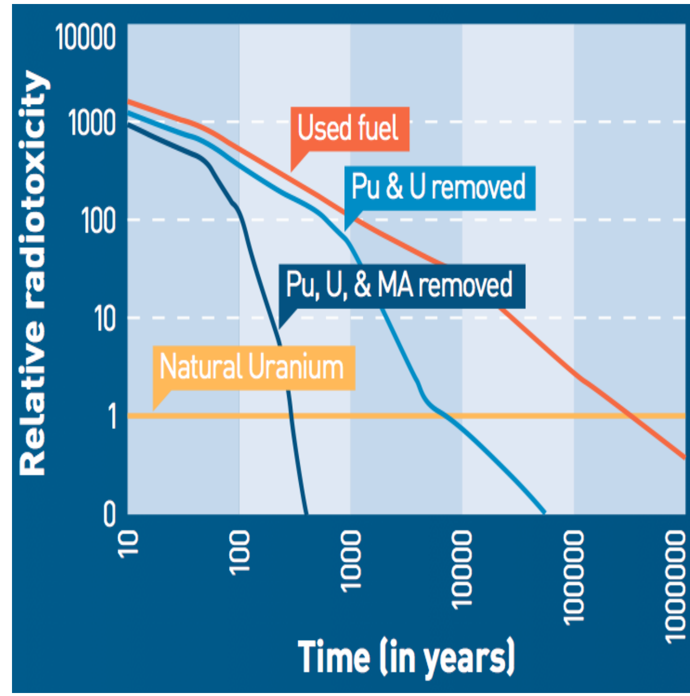
- The giant research accelerator like CERN's Large Hadron Collider in Geneva, with its 27 km is only the tip of the iceberg
- An accelerator can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, besides discovering the secrets of the Universe
- Medical and industrial markets exceed $3.5 billion/y, and are growing at more than ten percent annually. Digital electronics now depend on particle beams for ion implantation, creating a $1.5 billion annual market for ion-beam accelerators. All the products that are processed, treated or inspected by particle beams represent a collective annual value of more than $500 billion.

Different activities

- Many nations have now recognized the potential for future applications of accelerators. European, US and Asian nations are already applying next-generation accelerator technology to current-generation challenges.
- For instance in March 2010, the Belgian government approved $1.3 billion for the MYRRHA project. an accelerator-driven system for producing nuclear power and transmuting nuclear waste that decays much faster into a stable non-radioactive form. The project will create 2000 long-term jobs.
- In China and Poland, accelerators are turning flue gases into fertilizer; and Korea operates an industrial-scale water-treatment plant using electron beams.
- Cancer patients in Japan and Germany and other European countries can now receive treatment with light-ion beams, and clinical centers with multiple ion beams.

Accelerators for transmuting nuclear waste

- A key challenge facing the nuclear fuel cycle is reducing the radio-toxicity and lifetime of spent nuclear fuel In the US alone,reactors will generate as much as 100,000 tons of total spent fuel over their lifetimes.
- The spent fuel from a light-water reactor must last about 1 million years to match the toxicity of natural uranium. Transmuting these isotopes into shorter-lived products would reduce this time to less than 500 years.



- An accelerator-driven subcritical system is ideally suited to burn the most problematic isotopes in spent fuel with a high-power proton accelerator to generate neutrons in a dense metal target.

Accelerators for fusion energy

- Nuclear fusion is potentially a clean and safe energy source. Two approaches are being developed worldwide:
  - low-pressure/long-confinement-time devices using magnetic field confinement;
  - and very-high-density/short-confinement-time devices using inertial confinement.
- Accelerator technology plays a key role in both, either as a supporting technology in certain aspects of plasma fusion, or as the central component for ion-beam-driven inertial fusion.
- Accelerators also play a central role in the development of materials required by both fusion and fission technologies with for instance of the International Fusion Materials Irradiation Facility, or IFMIF, with the challenging accelerator technology that supports it.

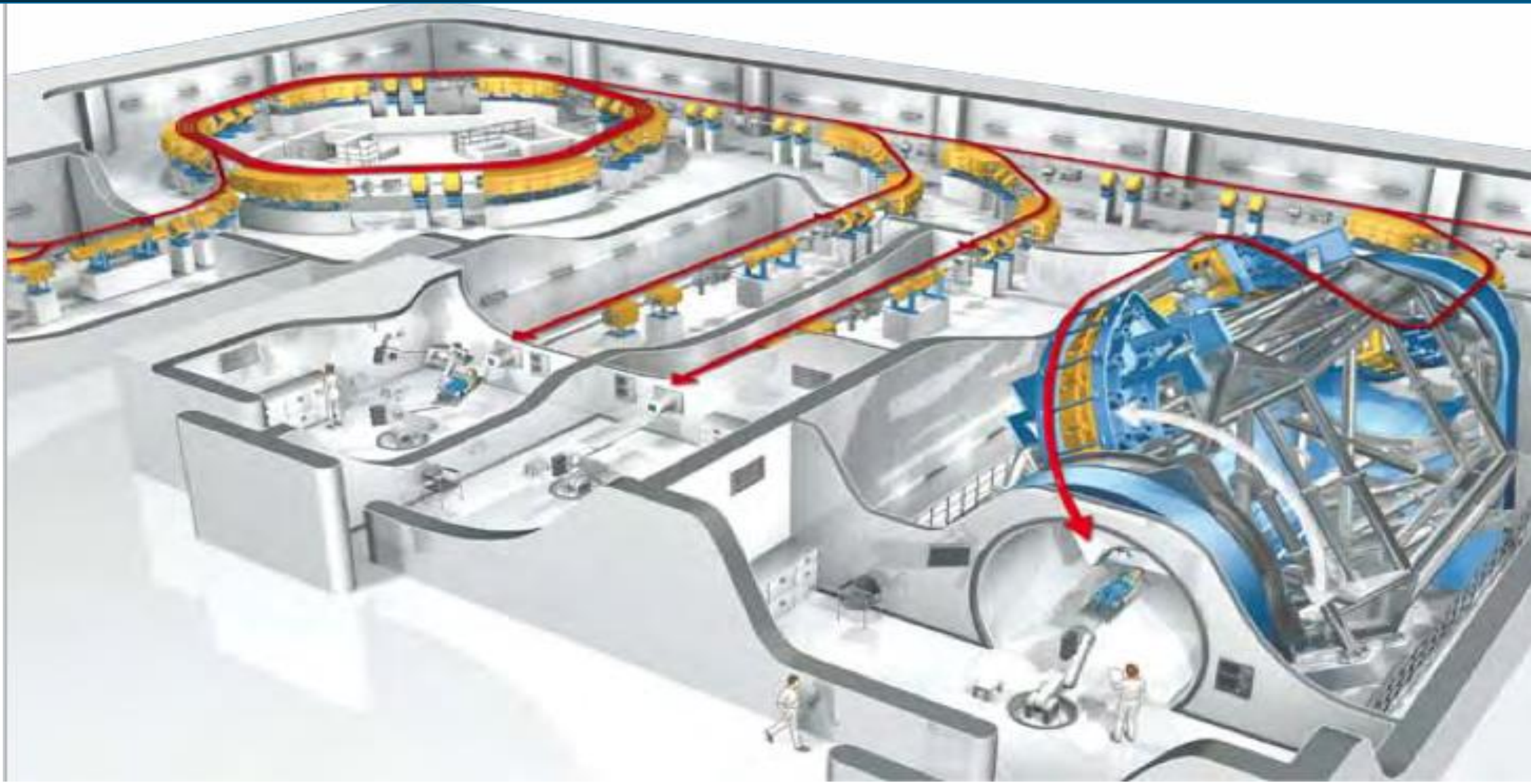
Accelerators for cleaner air and water

- Accelerators for treating *flue gas* need ~0.8 MeV beam energy and ~1 megawatt total installed electron beam power per 100-megawatt plant.
- For use in *water treatment*, the beam energy is less than 5 MeV, with beam power ranging from 0.4 megawatts for a small plant to 20 megawatts for a large water-treatment plant.
- Pilot plants exist or are under development in Poland, Bulgaria and China and an industrial-scale water treatment is in Korea.
- The treatment begins with a conditioning tower (1) that cools the flue gas. The cooled gas moves into an accelerator (2), where an electron beam triggers a chemical reaction (3) to convert the sulfur dioxides and nitrogen oxides into ammonium sulfate and ammonium nitrate. The electrostatic precipitator (4) removes the sulfate and nitrate as products to be sold to fertilizer companies. The clean gas goes out the chimney stack (5).

Accelerators for Medicine

- Circular and linear electron accelerators have been developed for clinical use in radiation therapy of tumours - already since the thirties - with the aim of achieving a high radiation dose in the tumour and as low as possible dose in the adjacent normal tissues.
- The treatment of a tumour needs a radiation dose of about 60 Gy which is given usually in daily fractions of one to two Gy.
- Today, from a region with a population of about one million, about 6000 patients per year need treatment for cancer. Half of them are treated by surgery, the other half with ionizing radiation.
- About two thirds of these patients can be cured, but a large number cannot be treated satisfactorily. The unintentional radiation reactions in the normal tissues adjacent to the tumour, however, very often lead to the death of the patient.
- New types of radiations such as neutrons, negative pions, protons and heavy ions are therefore being studied.

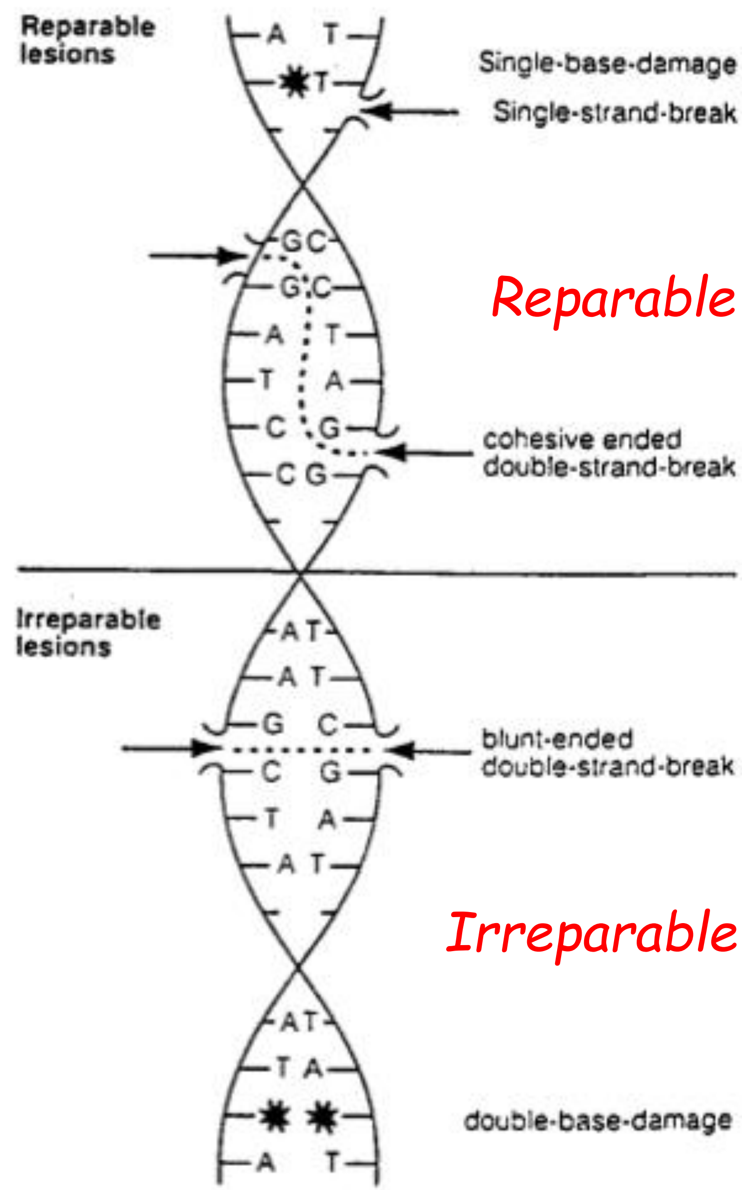
Example of accelerator driven Ion Therapy



- The Heidelberg Ion Therapy Facility has ion capability from protons to carbon. It includes two fixed-beam rooms and one rotating gantry suitable for carbon beams. *T. Haberer, Heidelberg*

Reparable and irreparable DNA lesions

- By the passage of an ionizing particle lesions in the DNA letters as well as in the backbone of the DNA may occur, some are reparable, others irreparable
- There is evidence of *a natural repair* of the radiation damage in living cells.
- Single strand breaks are reparable. Double staggered-ended breaks are also reparable if diagonal in the DNA.
- The ends of a double strand local break, diffuse away from each other very quickly and therefore are irreparable.
- Densely ionizing radiations, (alpha particles or protons) are preferable with preferentially irreparable lesions.



Proton driven medical therapy

- As of January 2016, there are over 45 particle therapy facilities worldwide. This represents a total of more than 121 treatment rooms available to patients. More than 96,537 patients had been treated.
- HIMAC, the Heavy Ion Medical Accelerator in Chiba, Japan, began in 1994 followed by many additional compact Accelerators. In Germany, the Heidelberg Ion-Beam Therapy (HIT) Center opened in 2009. In Italy, France, Austria and China many ion-beam centers are under construction or operation.
- However the issue of when, whether, and how best use either surgery or proton therapy is still controversial. For instance, in the case of prostate cancer, the most common indication for proton beam therapy, no clinical study directly comparing proton therapy to surgery, brachytherapy, or other treatments *has shown any additional clinical benefit for proton beam therapy.*

Conclusions

- Particle colliders have been in the forefront of scientific discoveries for more than half a century. The accelerator technology has progressed immensely, while the beam energy, luminosity, facility size and the cost have grown by several orders of magnitude. Essential contributions have expanded many different fields of applications.
- A quick glance shows that since the 1930's, the energies achieved by particle accelerators have grown exponentially with time, with an increase by a factor of ten every seven years.
- These increases were always due to new ideas, and development and use of new technologies.
- *As we look to the future, one thing is certain: as long as we continue to make use of new technologies and ideas, new particle accelerators will continue to unpack unique and fundamental properties in Science and Technology.*

Thank you !

"I'm starting to get concerned about global warming."