Helium Liquefaction and Refrigeration since 102 Years

Hans Quack

CERN, 02.09.2010

Discovery of Helium

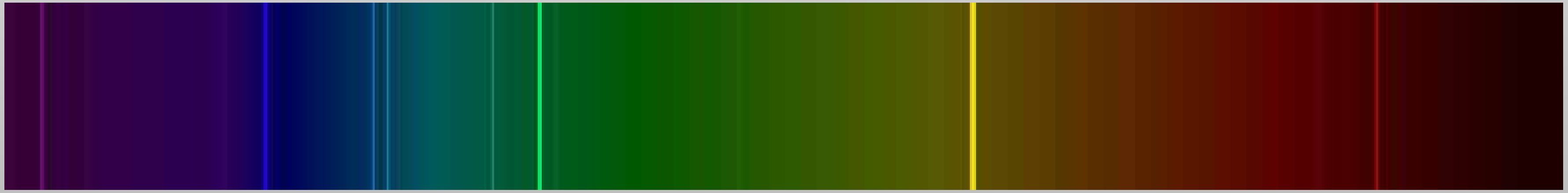
18.08.1868 During an eclipse of the sun in Guntoor/India the French astronomer Pierre Janssen observes a so far unknown bright yellow spectral line at 587,49 nm. Shortly afterwards the same line was detected by the English scientist Norman Lockyer (later Sir Norman Lockyer).

Lockyer together with his colleague Edward Frankland proposed to name the new element „helium“ – the element of the sun.

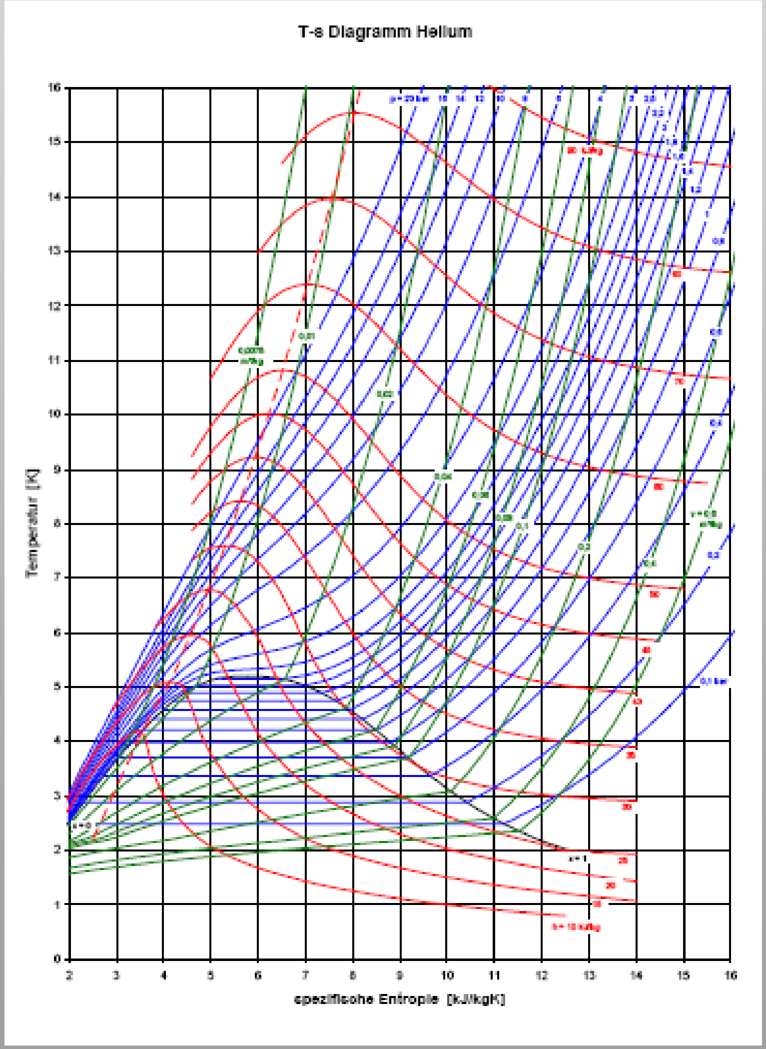
In 1882 L. Palmieri succeeded to detect spectroscopically helium also in the earth atmosphere.

In 1895 the British chemist William Ramsay succeeded to isolate small quantities of helium, originating from an uranium mineral.

Emission Spectrum of Helium



This is a colour representation of the emission line spectrum of neutral and ionized Helium excited in a electrical discharge. A faint continuum is added only to give a better impression of the location of the colours in the spectrum.

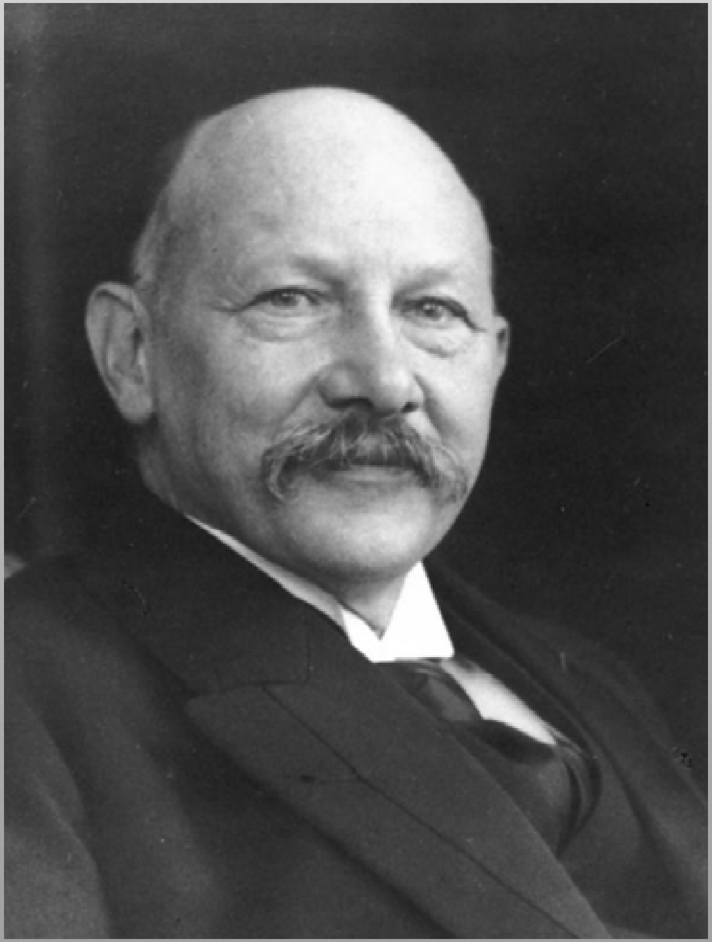


Van der Waals had detected that all substances have similar state diagrams. (Theory of corresponding states).

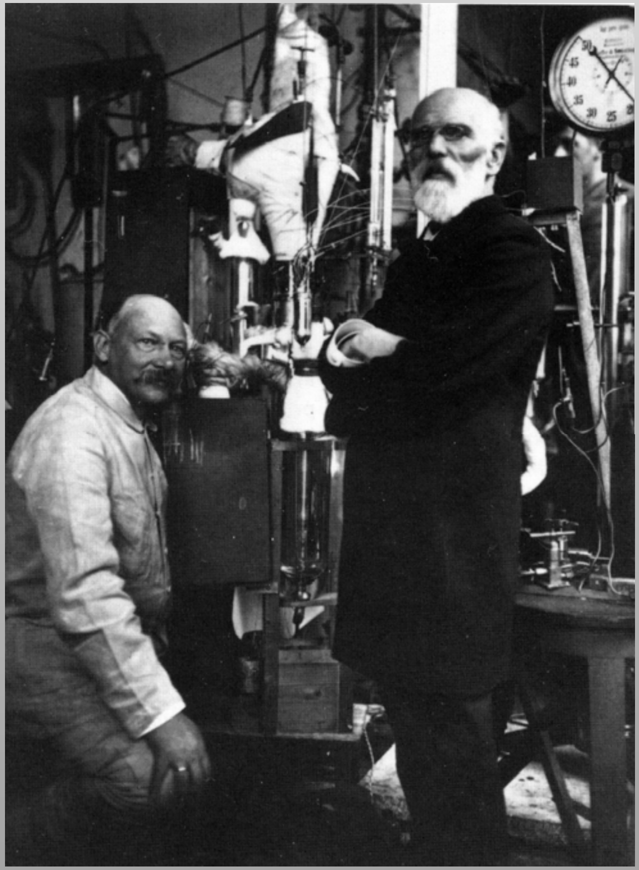
From measuring the thermal properties of helium at liquid hydrogen temperatures, scientists tried to predict the temperature of the critical point of helium.

1896	Olszewski (Cracow)	Tc < 9K
1901	Dewar (London)	Tc < 9K
1905	Olszewski (Cracow)	Tc < 2K
1907	Van der Waals	Tc < 6 K

Heike Kamerlingh Onnes



- 1837 Van der Waals born in Leiden
- !853 Kamerlingh Onnes born in Groningen
- 1877 Van der Waals, Prof. Exp. Physics, Amsterdam
- 1882 K. Onnes, Prof. Exp. Physics, Leiden
- 1895 C. Linde and Hampson liquefy air with JT process
- 1898 Dewar liquefies Hydrogen via JT expansion
- 1907 Van der Waals's equations yield Tc of 6K for He
- 1908 K.Onnes liquefies helium
- 1910 Van der Waals awarded Nobel Prize in Physics
- 1913 K.Onnes awarded Nobel Prize in Physics



Kamerlingh Onnes and Van der Waals, 2008

Helium compressed by mercury pump to 20 bar and higher.

Successive cooling by:

LAir at 79 / 1.0 K / bar

Hampson regenerative HE 1.

LH2 at 20 / 1.0 K / bar

LH2 at 14 / .07 K / bar

Hampson regenerative HE 2.

JT expansion to 4.2 / 1.0 K / bar

Liquid Helium at 4.2K (Tc / Pc=5.2 / 2.3 K / bar)

Liquid Helium by cascade and JT expansion.

Gas and material resources in 1908

Large chemistry lab.needed. To make and purify all gases used in cascade liquefiers.

Helium only from monazite sand at 1L gas per kilogram of sand, ie. 1L liquid per tonne of sand.

Helium production from Natural Gas started 1917.

Thermometry via Constant Volume gas and Pt resistance devices.

No steels or aluminium alloys. No welding.

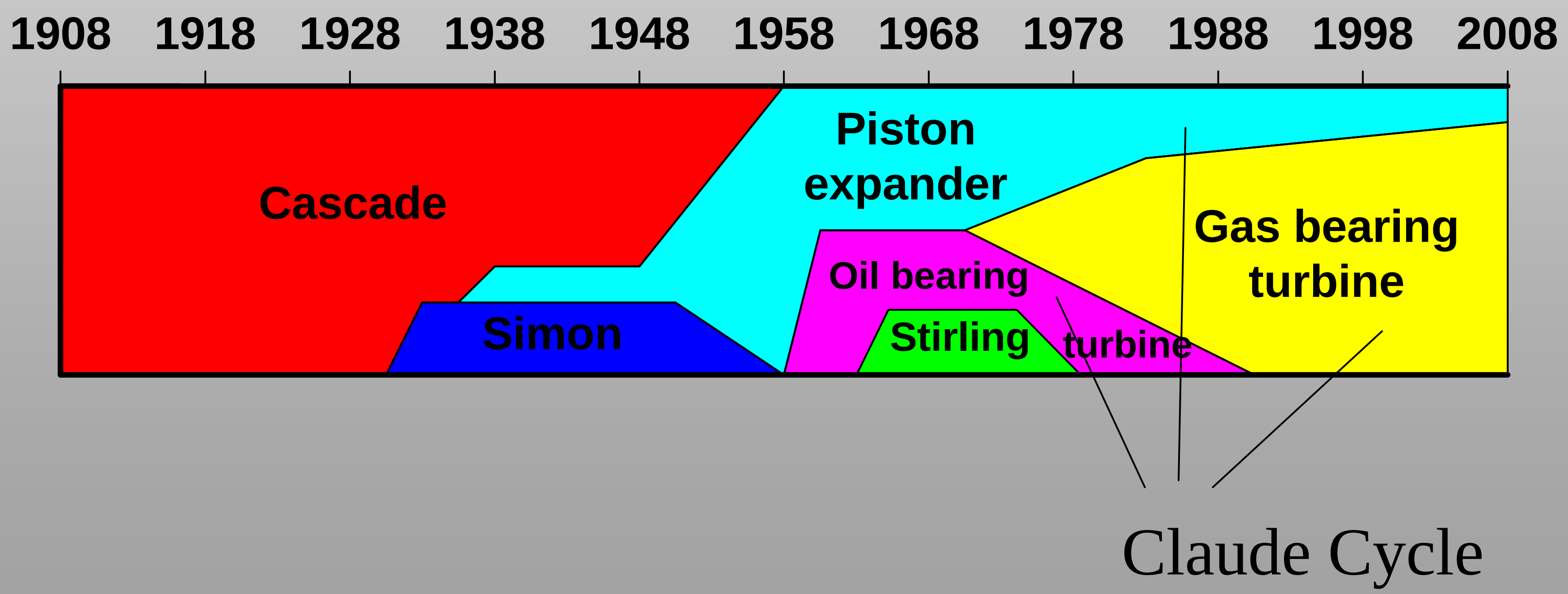
Ni alloys like German Silver; Copper alloys like brass; high k copper, available. Soft/hard soldering of joints, only.

High borosilicate Pyrex glass was standard for cryostats but was permeable to He gas. Low borosilicate Monax was found to be non-permeable to helium and later replaced Pyrex.

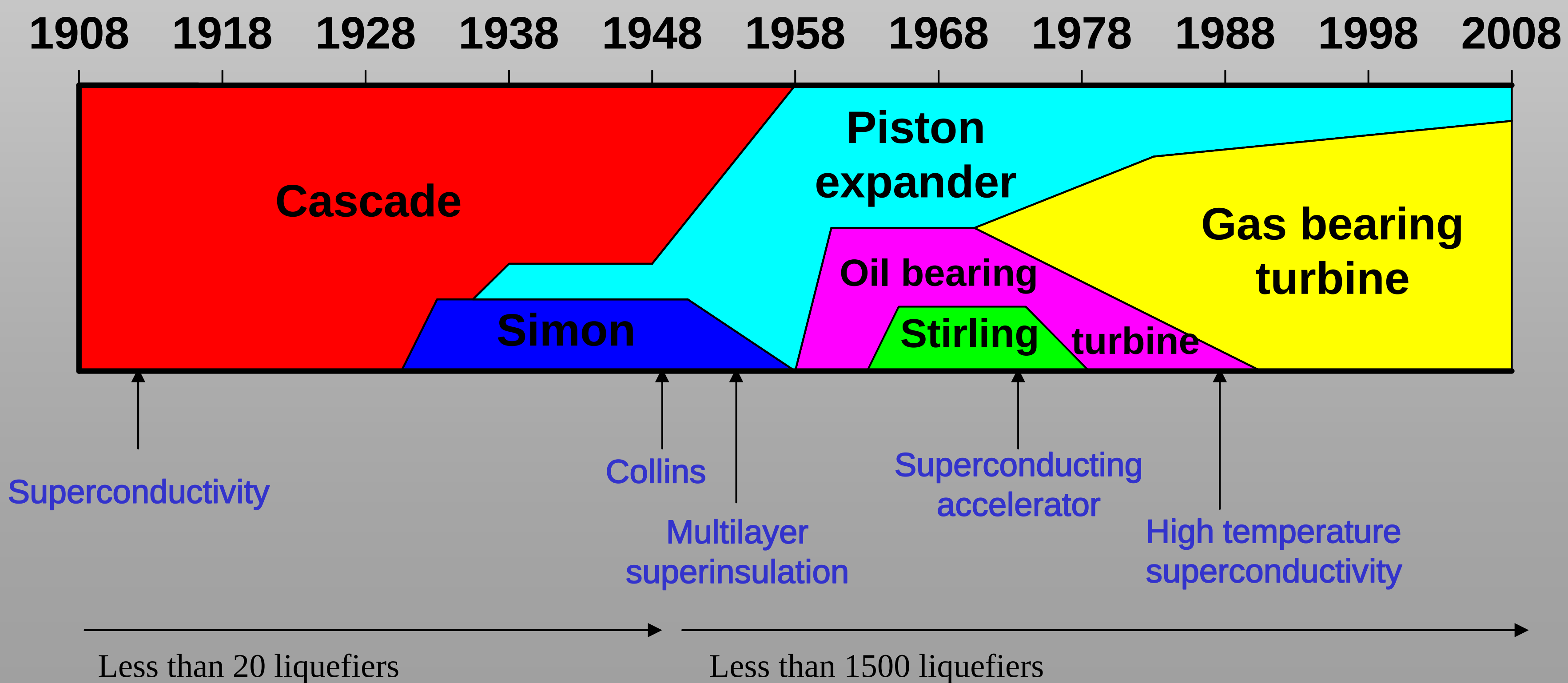
By mid 1950's, availability of gases, LIN and LHe began to improve. Glass replaced by cryogenic steels and aluminium alloys, with shielded-arc welding for joining. 1970's saw advent of digital voltmeters, PSD's, etc, for precision measurements.

Simulated photograph of the first Solvay conference in 1911 at the Hotel Metropole. Seated (L–R): W. Nernst, M. Brillouin, E. Solvay, H. Lorentz, E. Warburg, J. Perrin, W. Wien, M. Curie, and H. Poincaré. Standing (L–R): , M. Planck, H. Rubens, A. Sommerfeld, F. Lindemann, M. de Broglie, M. Knudsen, F. Hasenöhrl, J.H. Jean, E. Rutherford, H. Kamerlingh Onnes, A. Einstein and P. Langevin.

Development of helium liquefaction technology during the last 100 years



Important events



Cascade liquefaction using liquid air (or nitrogen) and liquid hydrogen precooling

After the first liquefaction of helium by Kamerlingh Onnes in 1908 it took 15 years until this was repeated in another laboratory. The cascade process was preferred by scientists, who had to design and build their liquefier themselves.

1923 Toronto (Mc Lennan)

1925 Berlin (Meissner)

1931 Washington (NBS)

1958 Beijing (CAS)

1960 Czechoslovakia (Rez)

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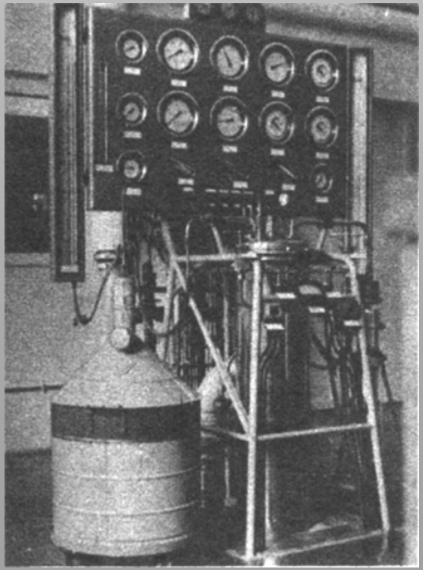
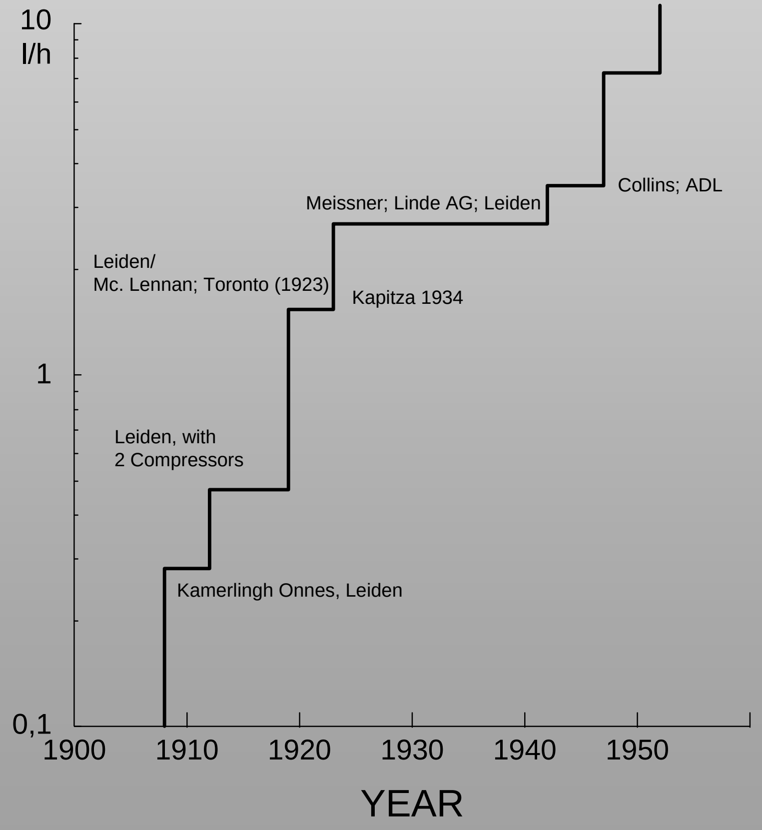


Cascade helium liquefier built in Czechoslovakia in 1960

Until 1945 the largest helium liquefier had a capacity of 3 l/h.

There were about 15 laboratories in the world, where liquid helium was available.



Isentropic Expansion

The use of isentropic expansion in liquefaction processes was known in cryogenics, since Claude and Heylandt used piston expanders in air liquefaction plants.

In helium liquefaction the development of suitable expanders turned out to be rather difficult.

The first step was a single expansion system developed by Franz Simon.

Franz Simon (later Sir Francis Simon):
Student of Nernst in Berlin,
since 1930 Professor for Physical Chemistry in Breslau,
emigrated in 1933 to Oxford.

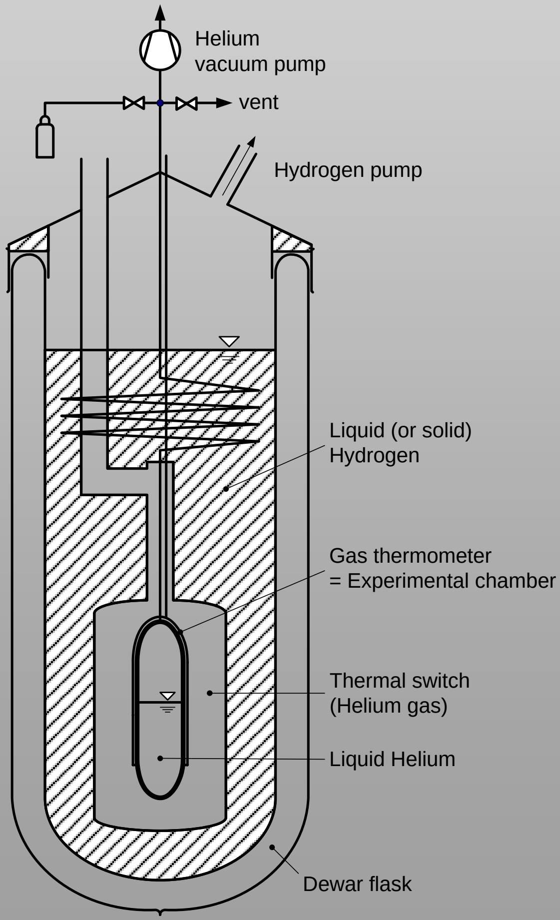
Simon developed a new type of simple helium liquefier between 1926 and 1932.

The Simon single expansion helium liquefier

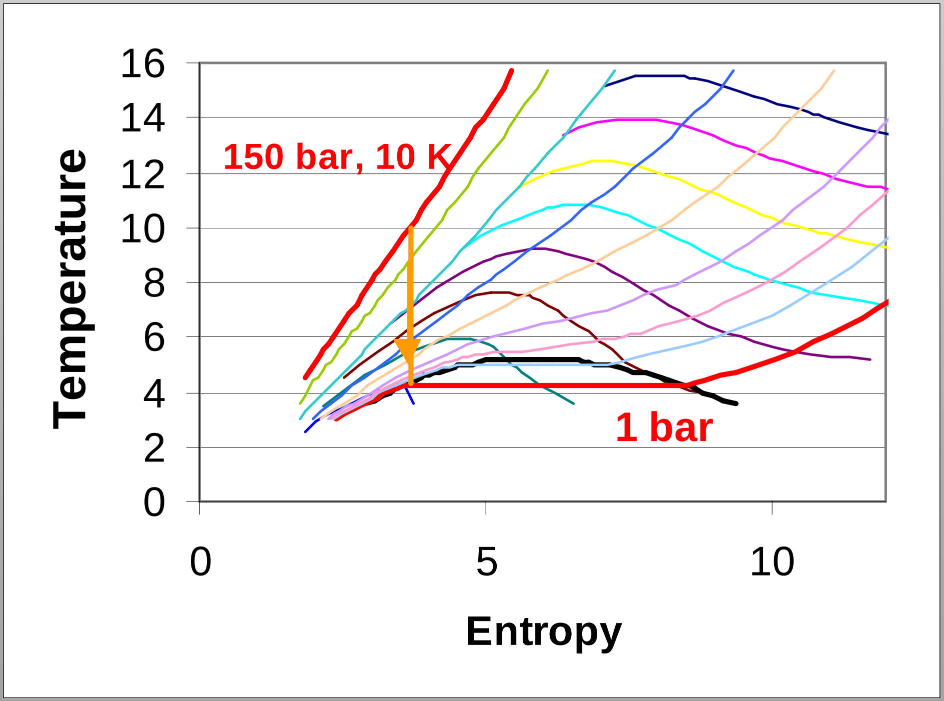
It consists of a high pressure container pre-cooled with solid hydrogen, which is filled with helium at high pressure; on slowly expanding the helium adiabatically, the remainder cools and liquefies so that the greater part of the container is filled with liquid helium.

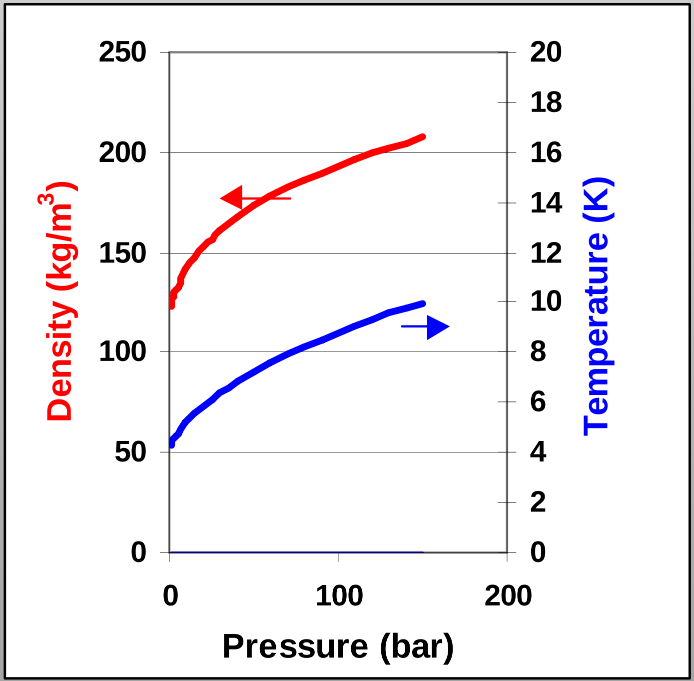
The container, now at liquid helium temperature, can thus be used as a cryostat for experiments.

This small, cheap liquefier was widely used until the 1950s in laboratories possessing no other source of liquid helium. At the Oxford Clarendon Laboratory there were often 12 such liquefiers waiting for the supply of liquid hydrogen.



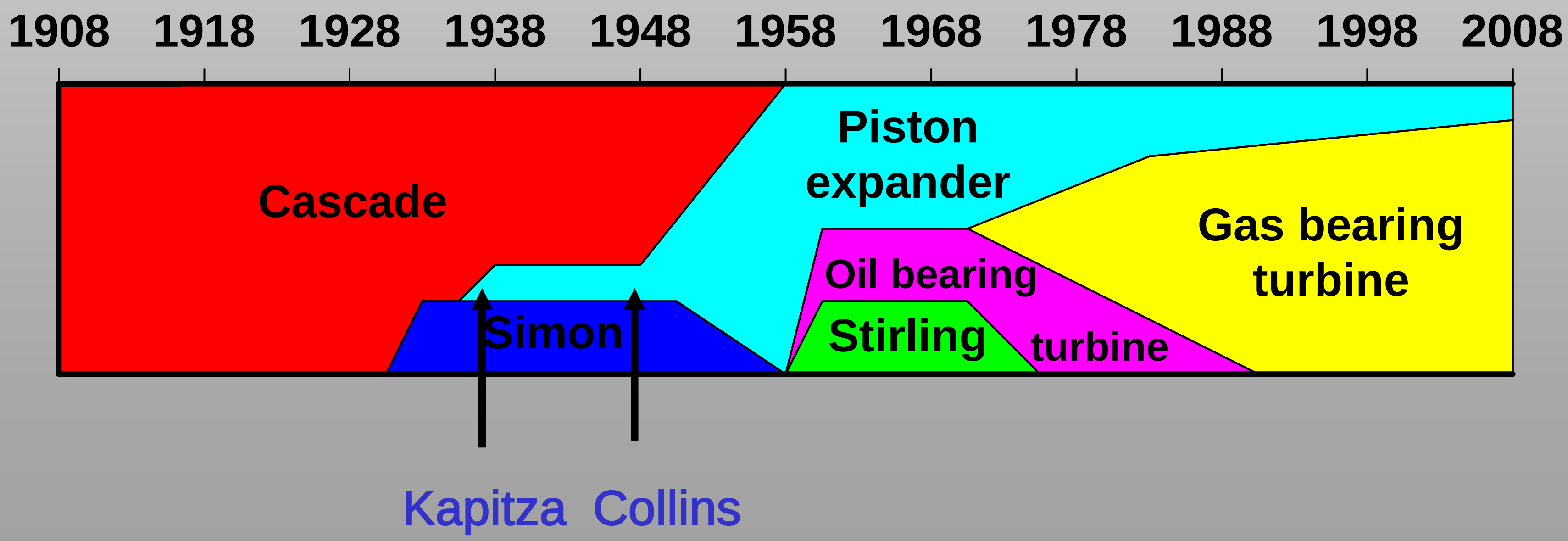
The high pressure helium gas was pre-cooled by pumping on liquid and solid hydrogen. Then the pressure in the vessel was slowly released.



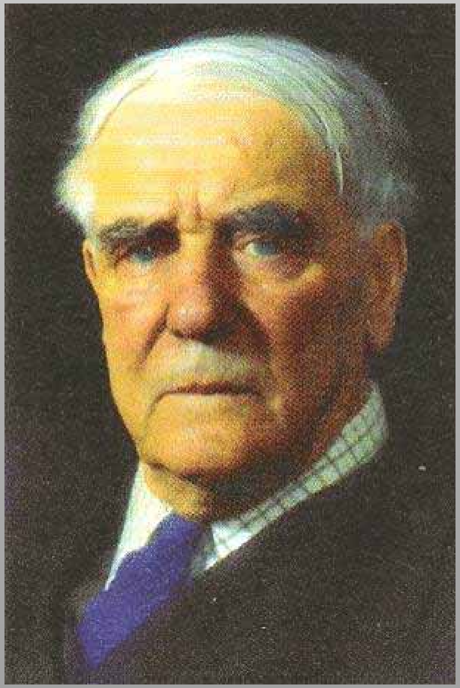


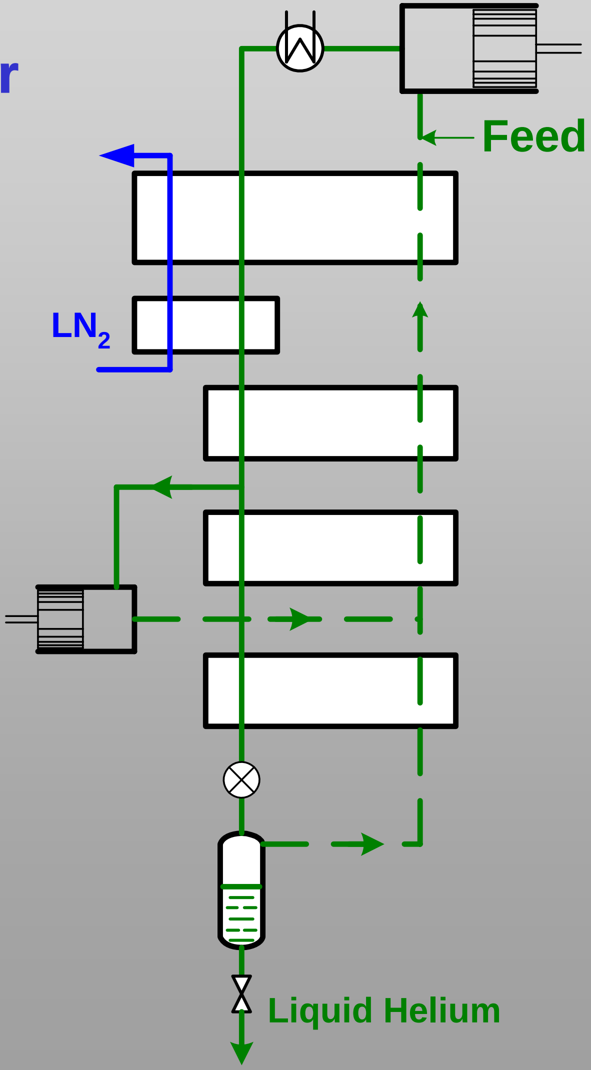
Starting the expansion with 150 bar and 10 K one obtains nearly of full vessel of liquid helium. The density changes from 205 to 125 kg/m^3.

Piston expanders are being introduced

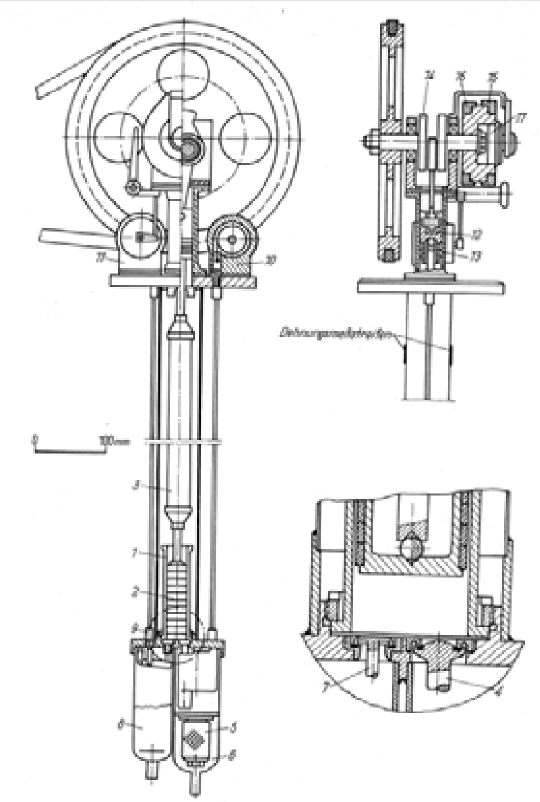


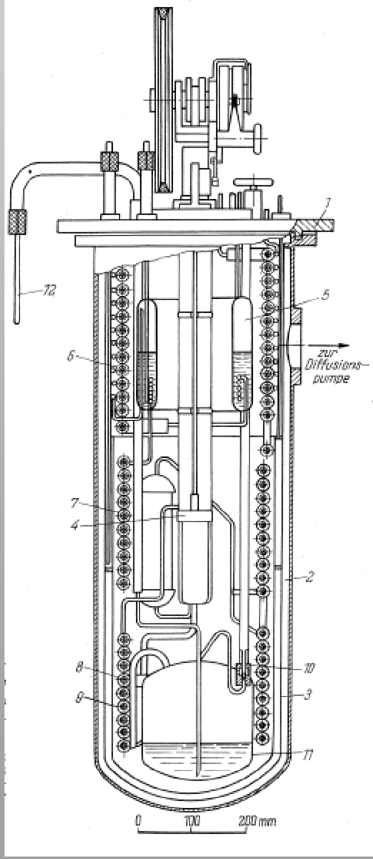
P. L. Kapitza: First helium liquefier with piston expander 1934 in Cambridge (UK)



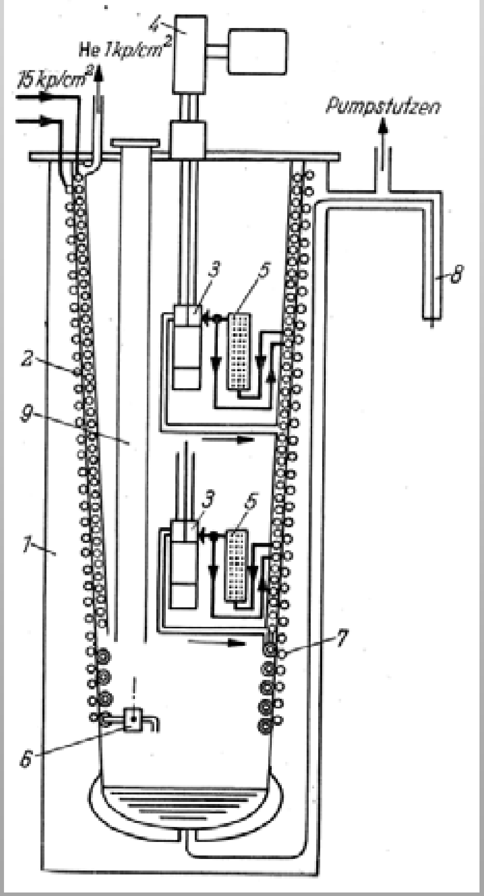


Piston expander and helium liquefier built under Kapitza's guidance at the Academy of Sciences of the USSR





Sam Collins, MIT



"Henry Ford did not make the first automobile, nor did Collins the first helium liquefier, but Collins can be compared to Ford in pioneering an efficient, economical, mass-produced machine for producing liquid helium."

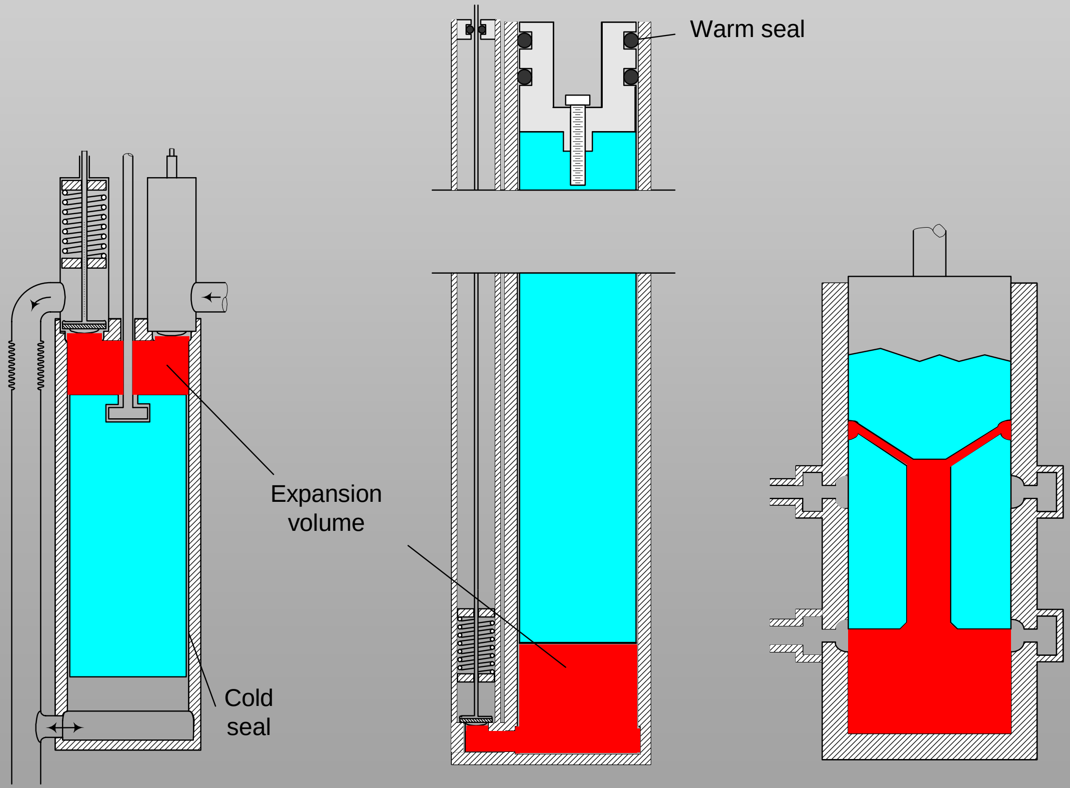
Scientist, who were lucky to get a Collins liquefier, often put on their Sunday suits, when operating the plant.

William Fairbank with new Collins liquefier (1952)

First Helium Liquefier in Japan (1952)

This Collins-type helium liquefier (made by A.D. Little Ltd., USA) was the first to be installed in Japan in 1952. This machine, having a liquefaction capacity of 4 liters/h at that time, made a great many contributions to the developments of low-temperature scientific researches at Tohoku University. Later the capacity was raised up to 8 liters/h due to the increase of the compressor.

Following Kapitza and Collins about 10 types of piston expanders were developed around the world

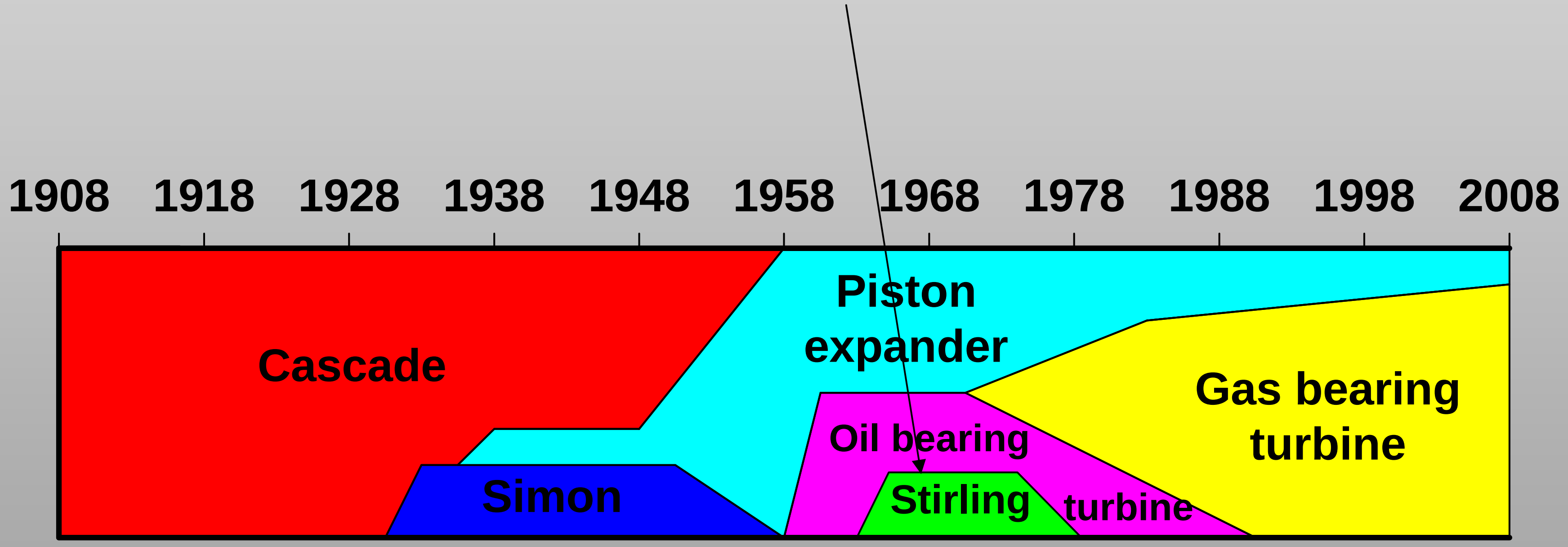


Piston rod under tension (cold seal)

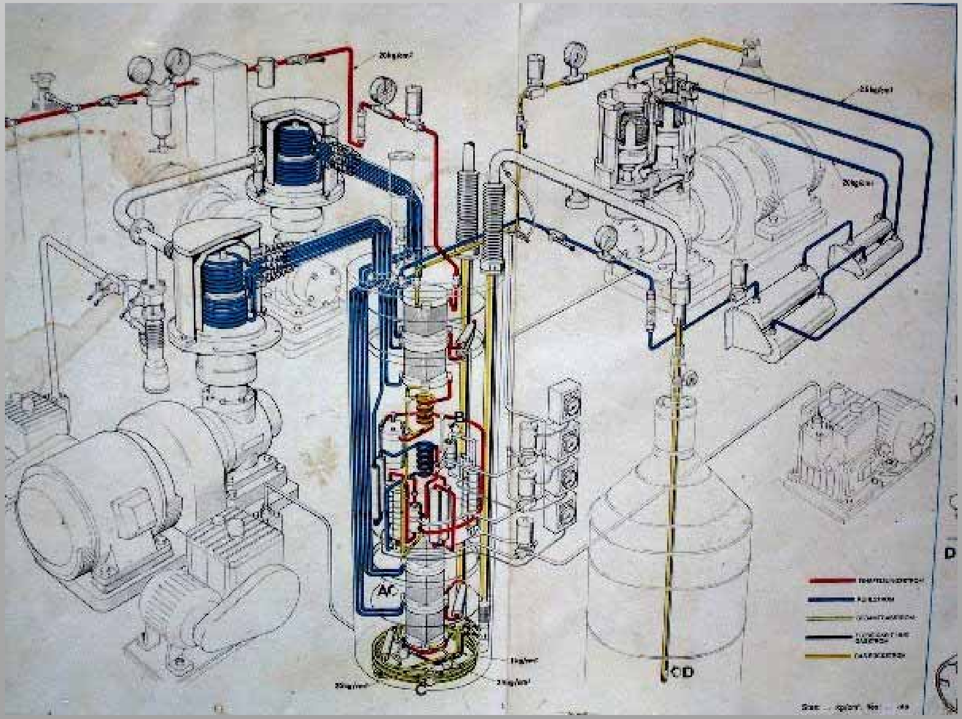
Piston rod under compression (warm seal)

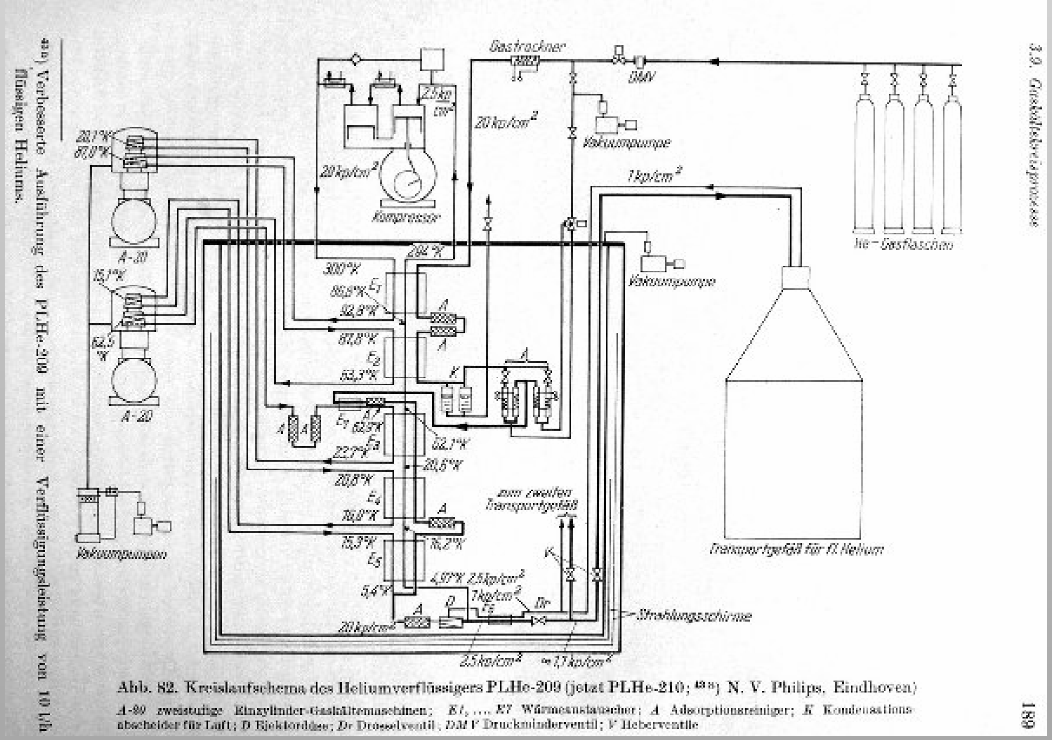
Valve-less piston expander (Doll-Eder)

Stirling technology



A two-stage Stirling helium liquefier was developed by the Phillips company





In the period between 1968 and 1978 about 70 Philips PLHe 209/210/212 were installed.

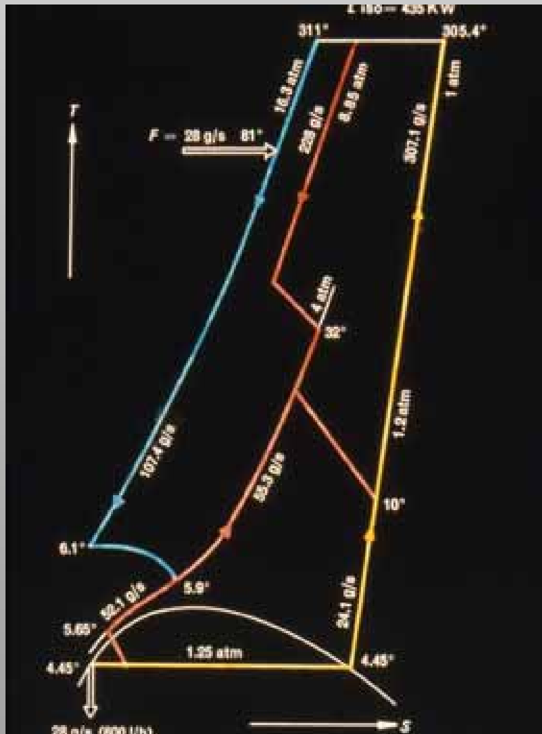
Until about 1953 liquid helium was only available in those laboratories, which had an own helium liquefier, since liquid helium could only be transported over relative short distances.

Superinsulation

The invention of multilayer superinsulation by Union Carbide around 1953 allowed shipment of liquid helium over longer distances, i. e. around the world.

Large helium liquefiers were built in the mid-west of the United States, mainly in support of the space program.

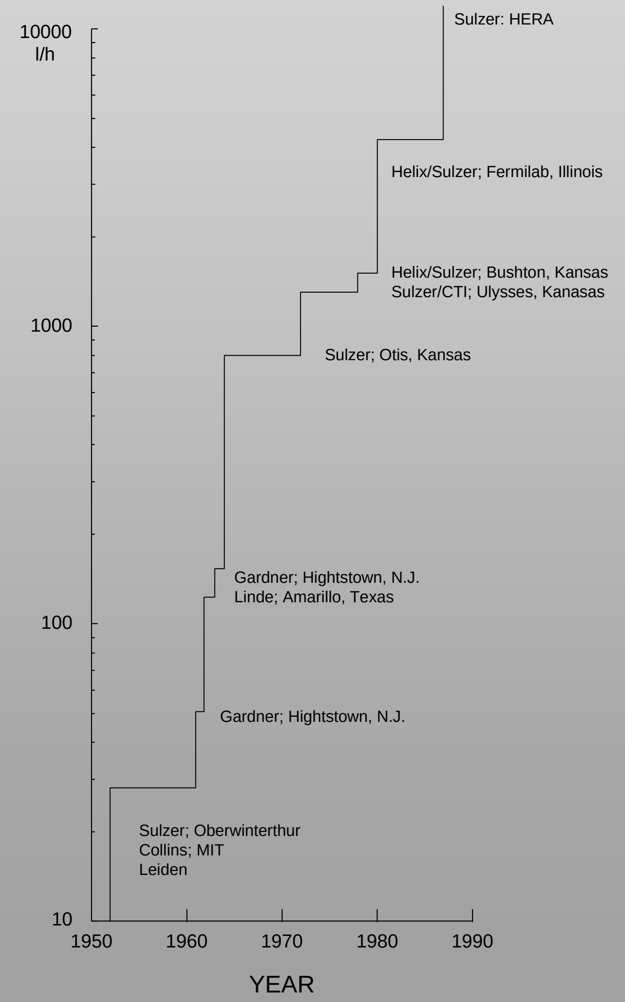
Large industrial liquefiers



800 l/h helium liquefier in Otis, Kansas, built in 1966

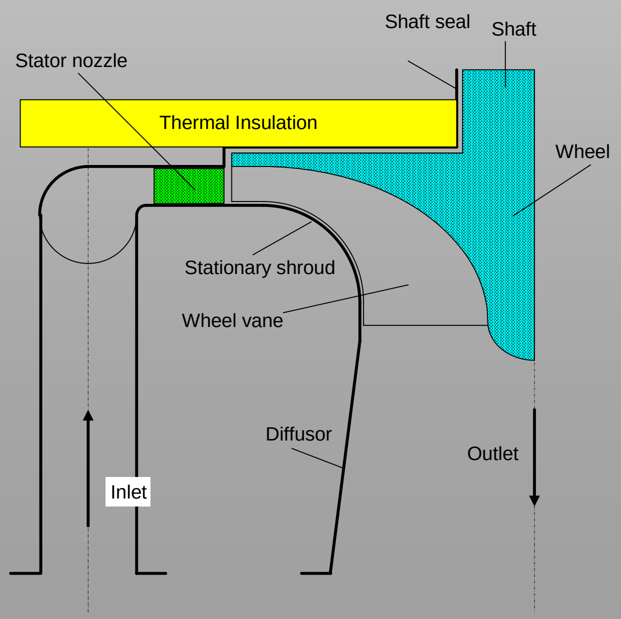
Large industrial liquefiers in the United States:
In the period between 1960 and 1975 the maximum size of helium liquefiers grew from 30 l/h to 1600 l/h.

The technology used was the Claude cycle with oil bearing turbines and non-lubricated piston compressors.

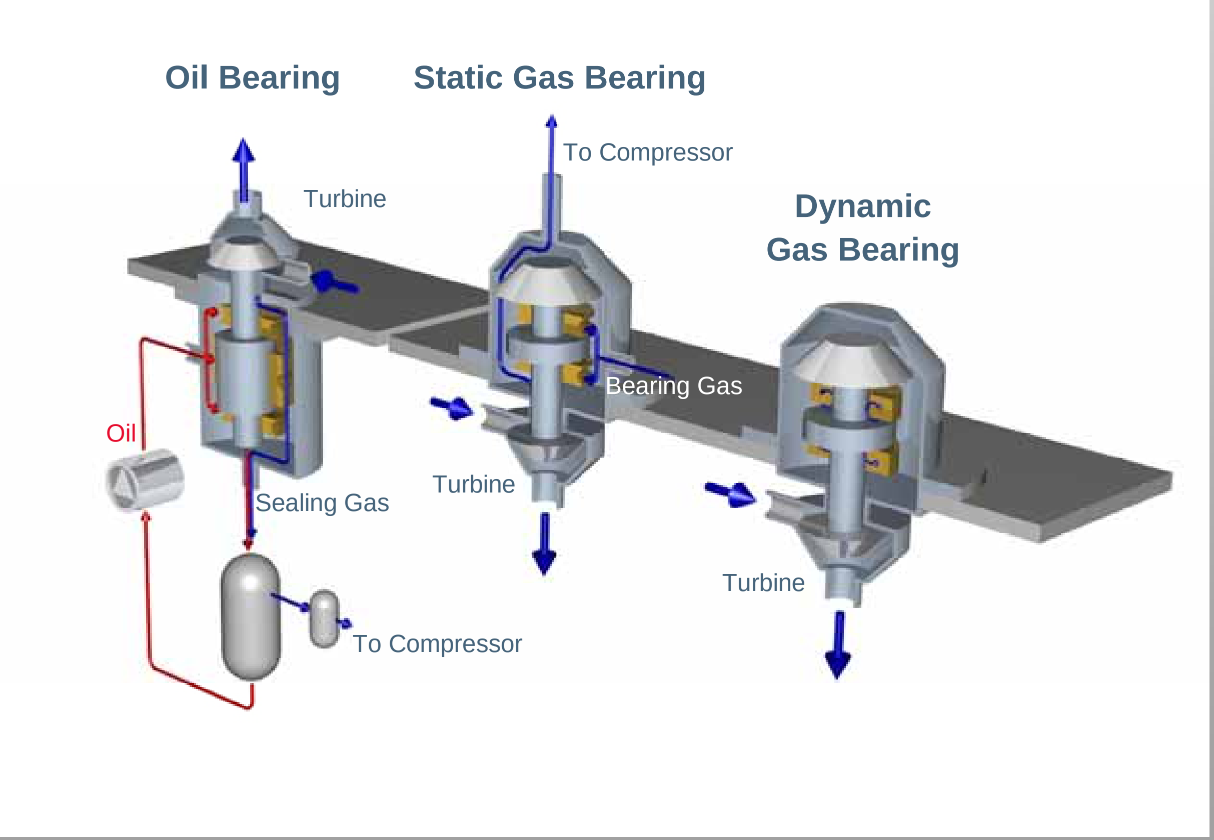


Cryogenic turbines: Peter Kapitza was the first to realize in 1937 a turbine expander for an air separation plant using a radial design with inward flow. In the 1950s – after quite some controversy - this technology was finally accepted in industrial air separation technology. There were a few special developments for the use of such turbines in hydrogen and helium liquefiers, which needed much higher circumferential speeds than in air separation plants.

Radial Expander: Components



Turbine Bearing Systems



Herby Sixsmith – the father of the gas bearing turbine

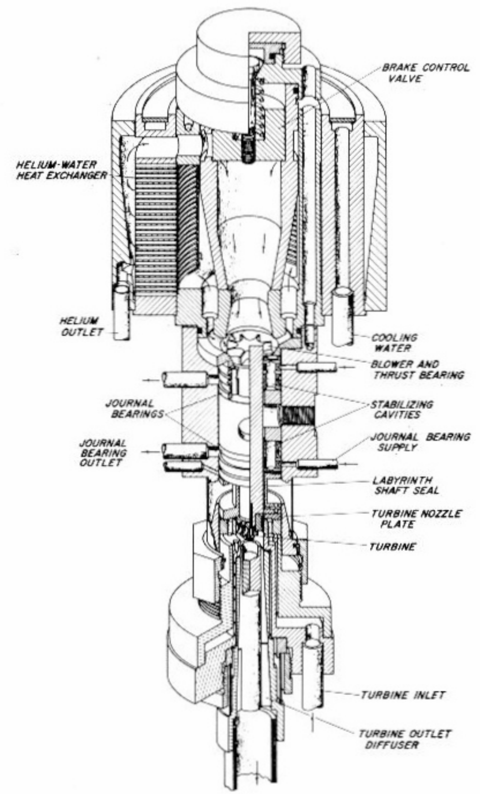


Figure 8-1. Turbine assembly.

Herby developed this turbine while on sabbatical at the NBS in Boulder. It used pressurized gas bearings. Shaft speed was 10,000 rev/s, shaft and turbine diameter 8 mm.

By this successful development many others were encouraged to start the development of similar turbines.

Following Sixsmith about ten types of gas bearing turbines were developed around the world.

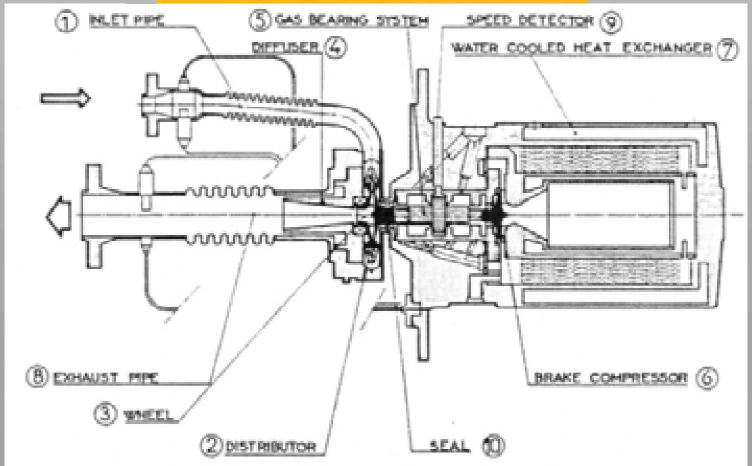
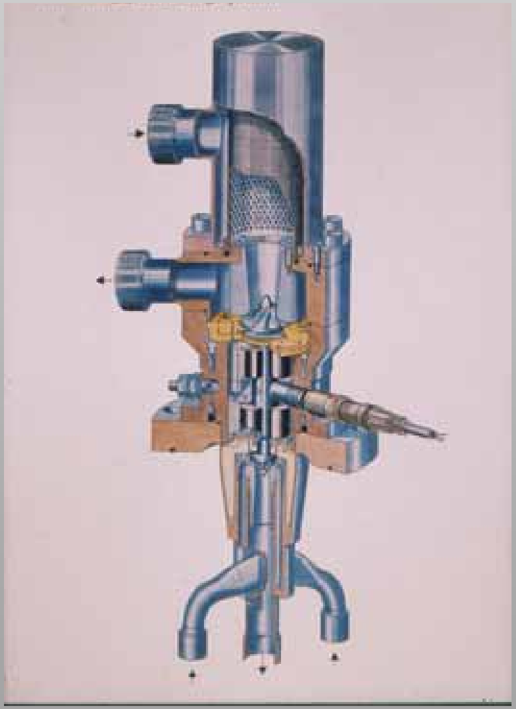


Fig. 1. Gas bearing cryogenic expansion turbine.

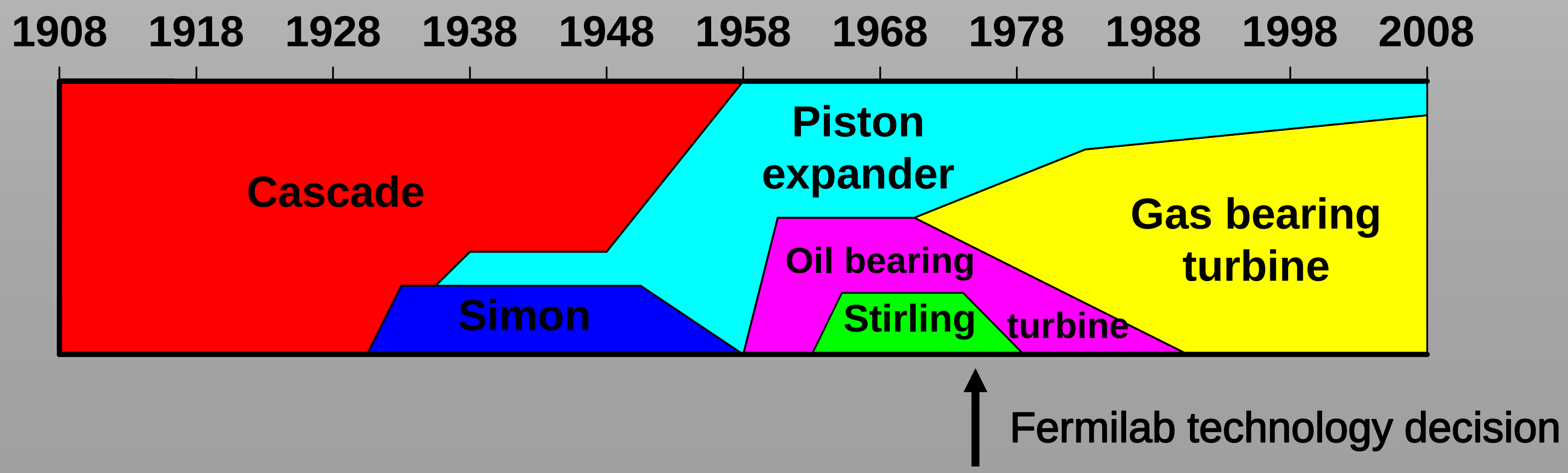


Superconducting Accelerators

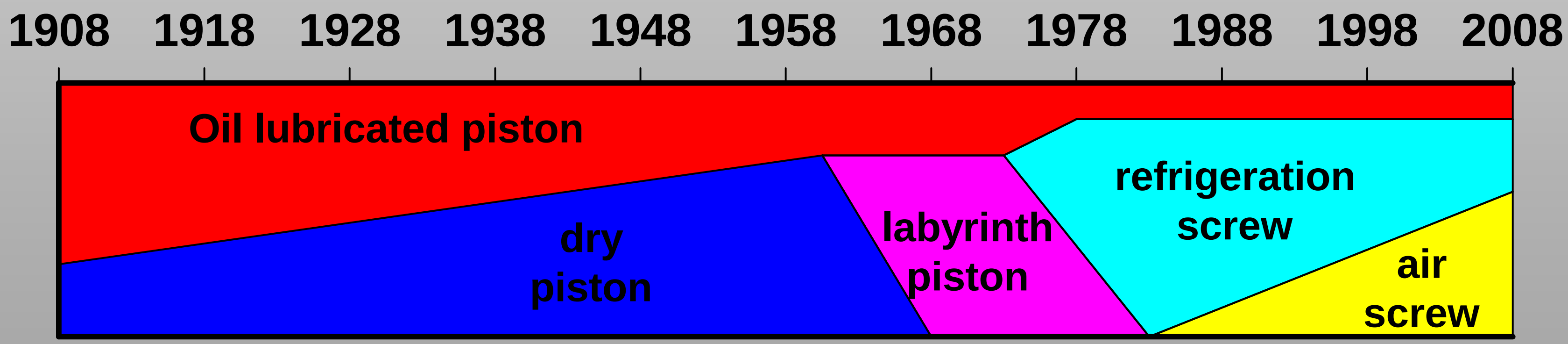
Progress in superconducting accelerator technology allowed in 1972 the decision to build the next large particle accelerator at Fermilab as a superconducting accelerator.

There were intensive discussions, which refrigerator technology should be used.

Even though a first 1500 W prototype refrigerator with gas bearing turbines was operated very successfully, the outcome was that a central liquefier was equipped with oil lubricated turbines and 24 satellite refrigerators were built with piston expanders.

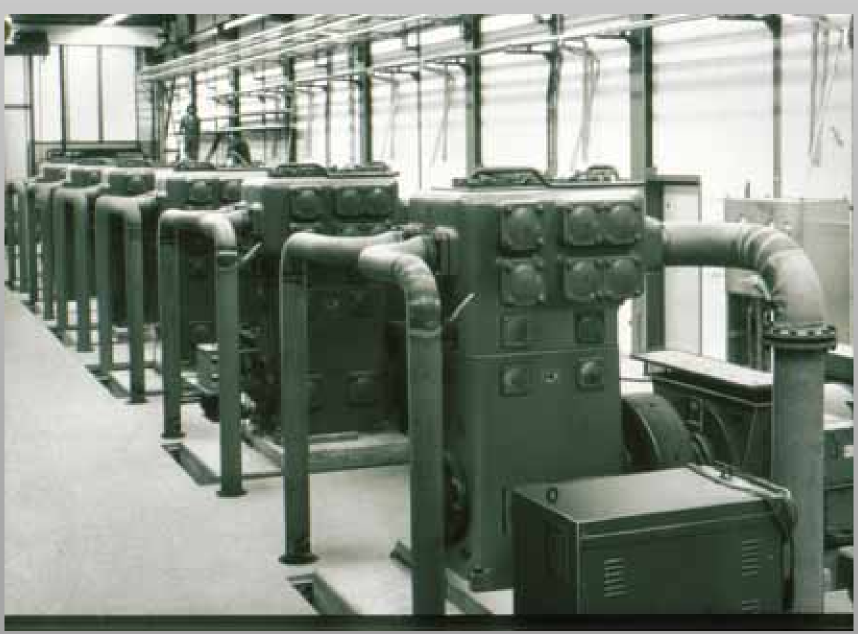


Types of compressors used for helium liquefiers



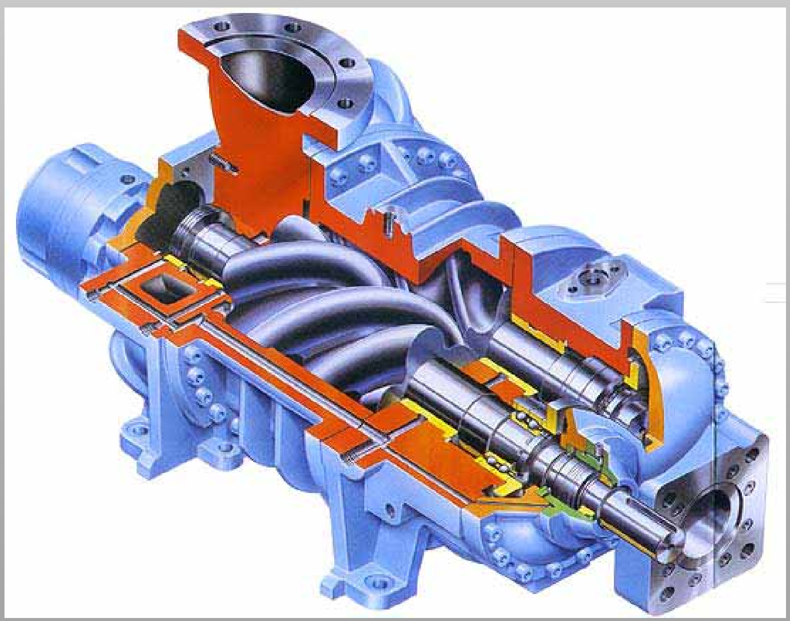
Piston Compressors

Horizontal lubricated

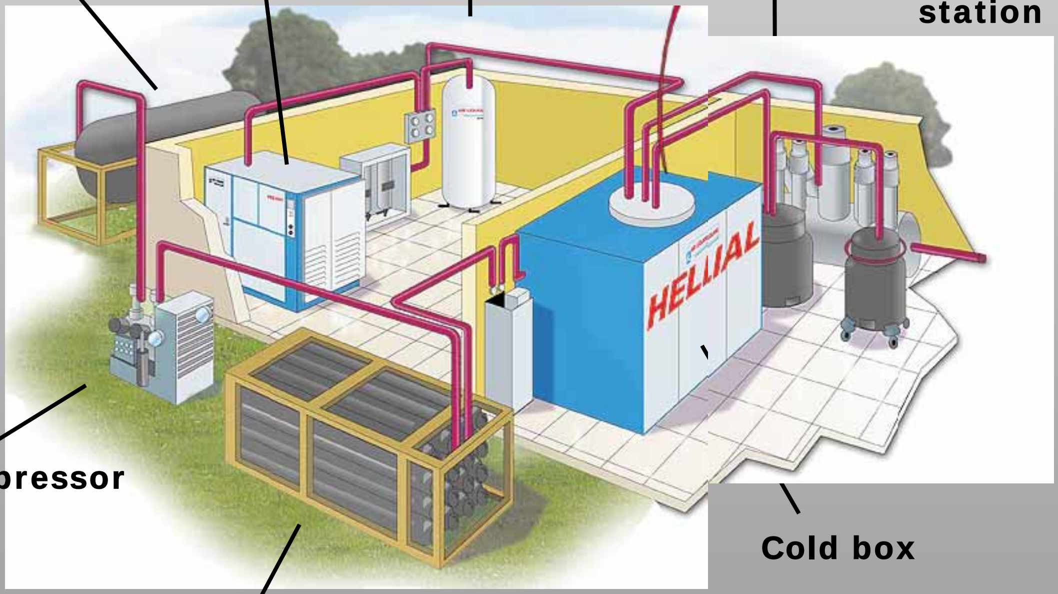


Vertical non-lubricated labyrinth piston seal

Refrigeration type screw compressors with slide valve

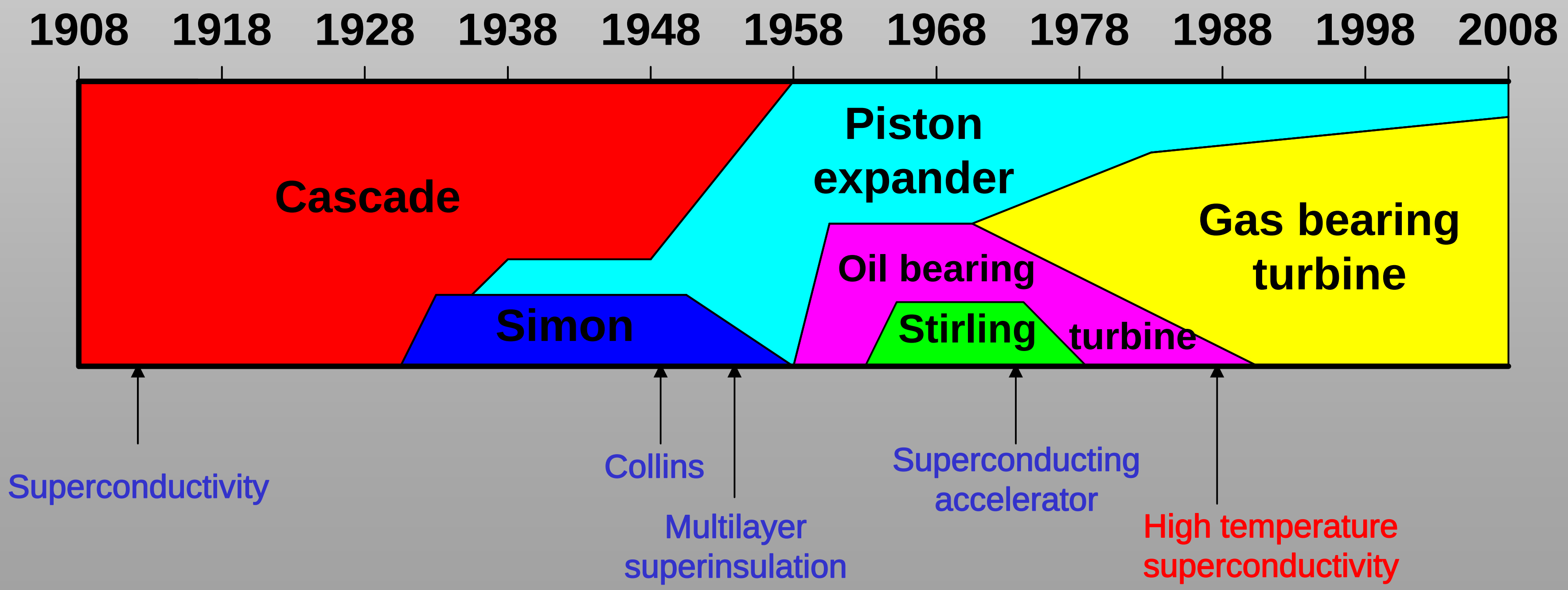


Most standard liquefiers nowadays use modified air screw compressors without slide valve. They have better efficiency and a lower price than screw compressors with slide valve.



Unfortunately there do not yet exist two-stage screw compressors without slide valve.

High temperature superconductivity

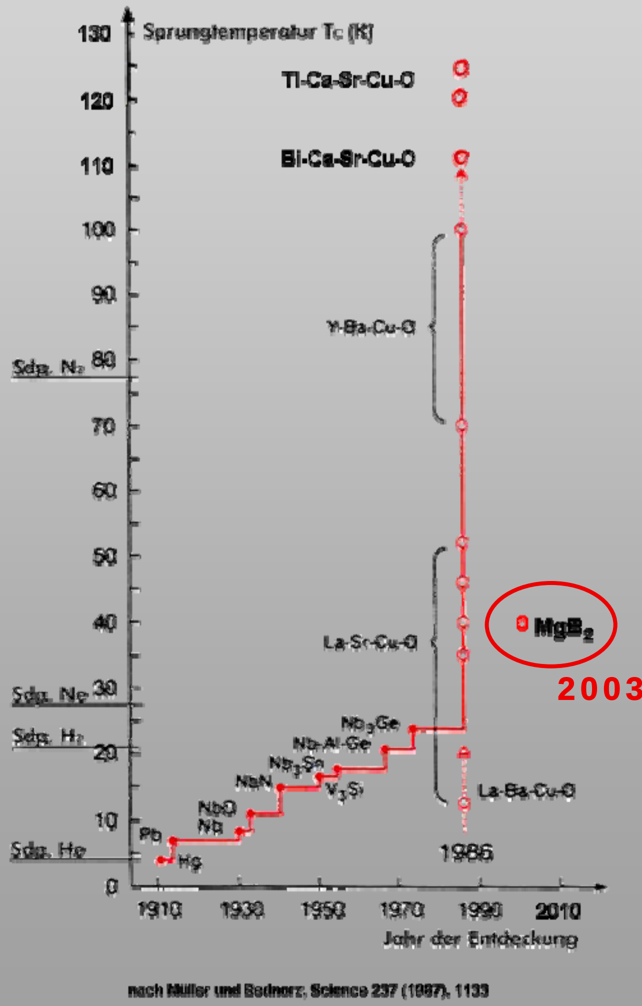


High temperature superconductivity

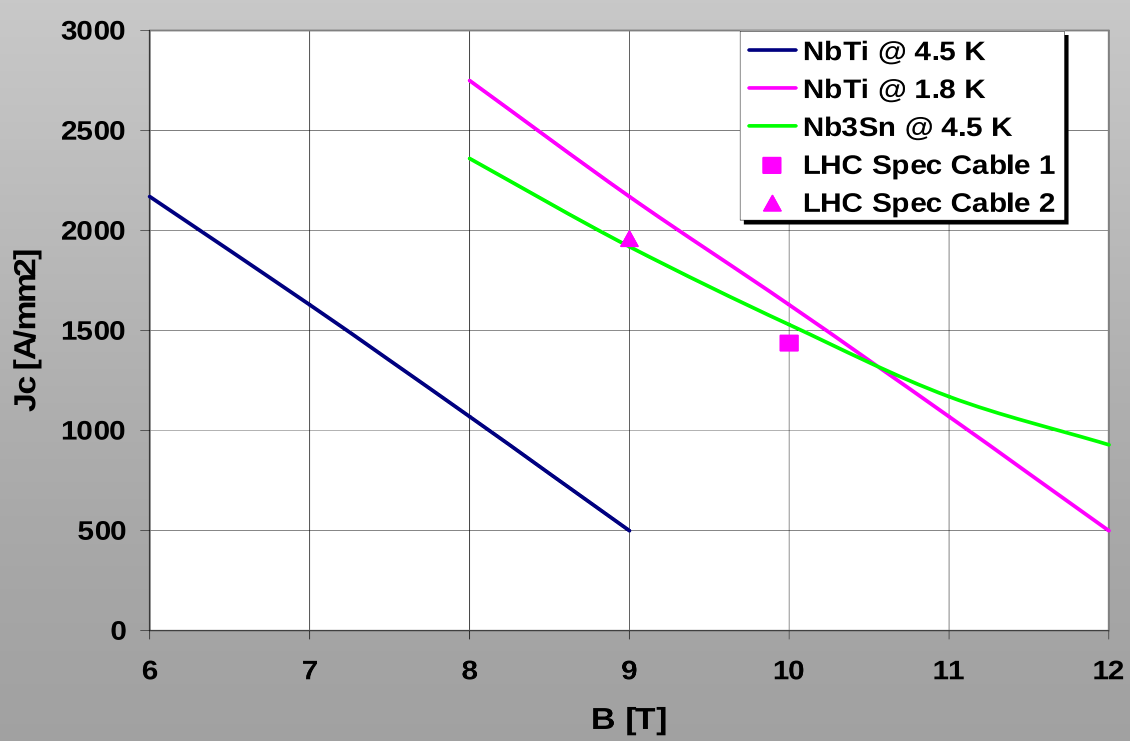
In 1986 high temperature superconductivity was detected.

„From now on we will not need the expensive and complicated liquid helium technology any more!“

But the opposite happened: Users of superconducting accelerators demanded lower and lower temperatures: 1,8 K instead of 4,2 K!

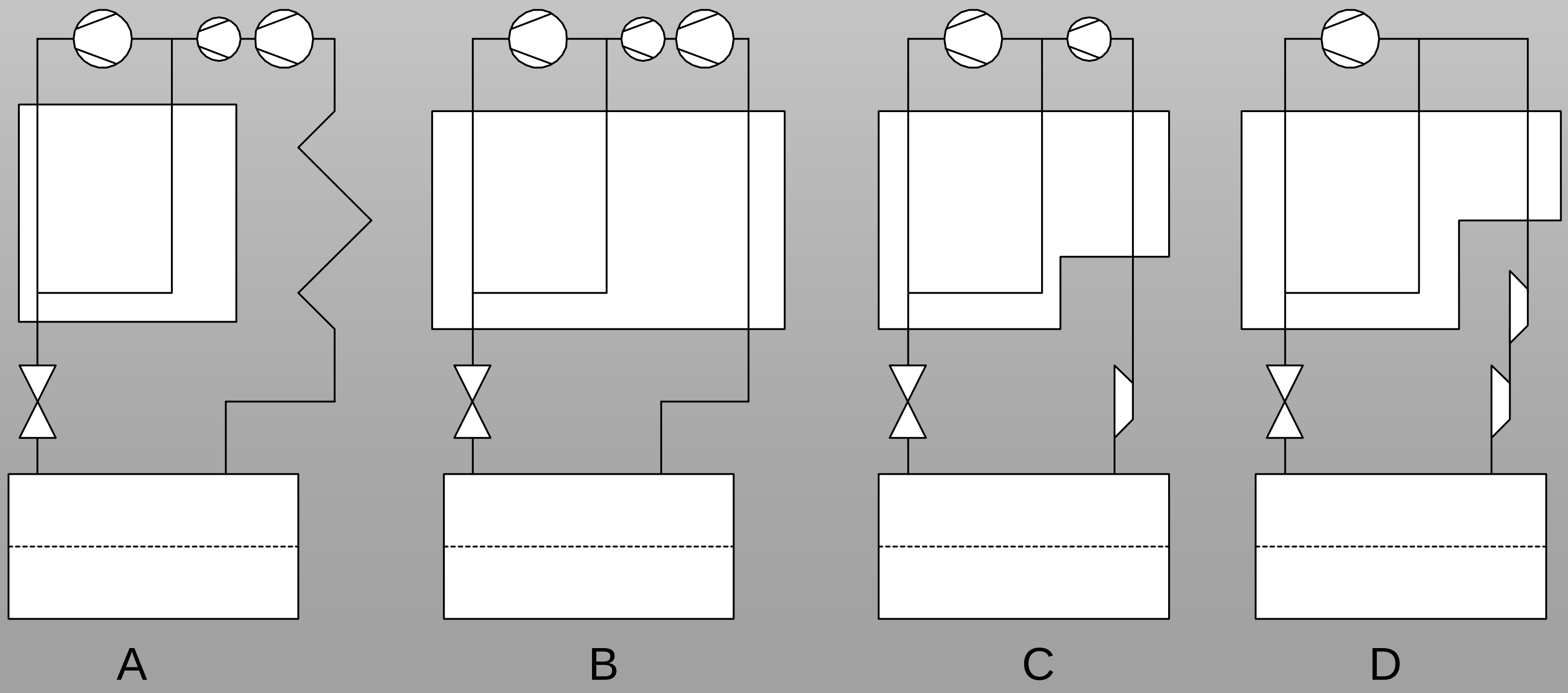


Critical Current Density of Technical Superconductors

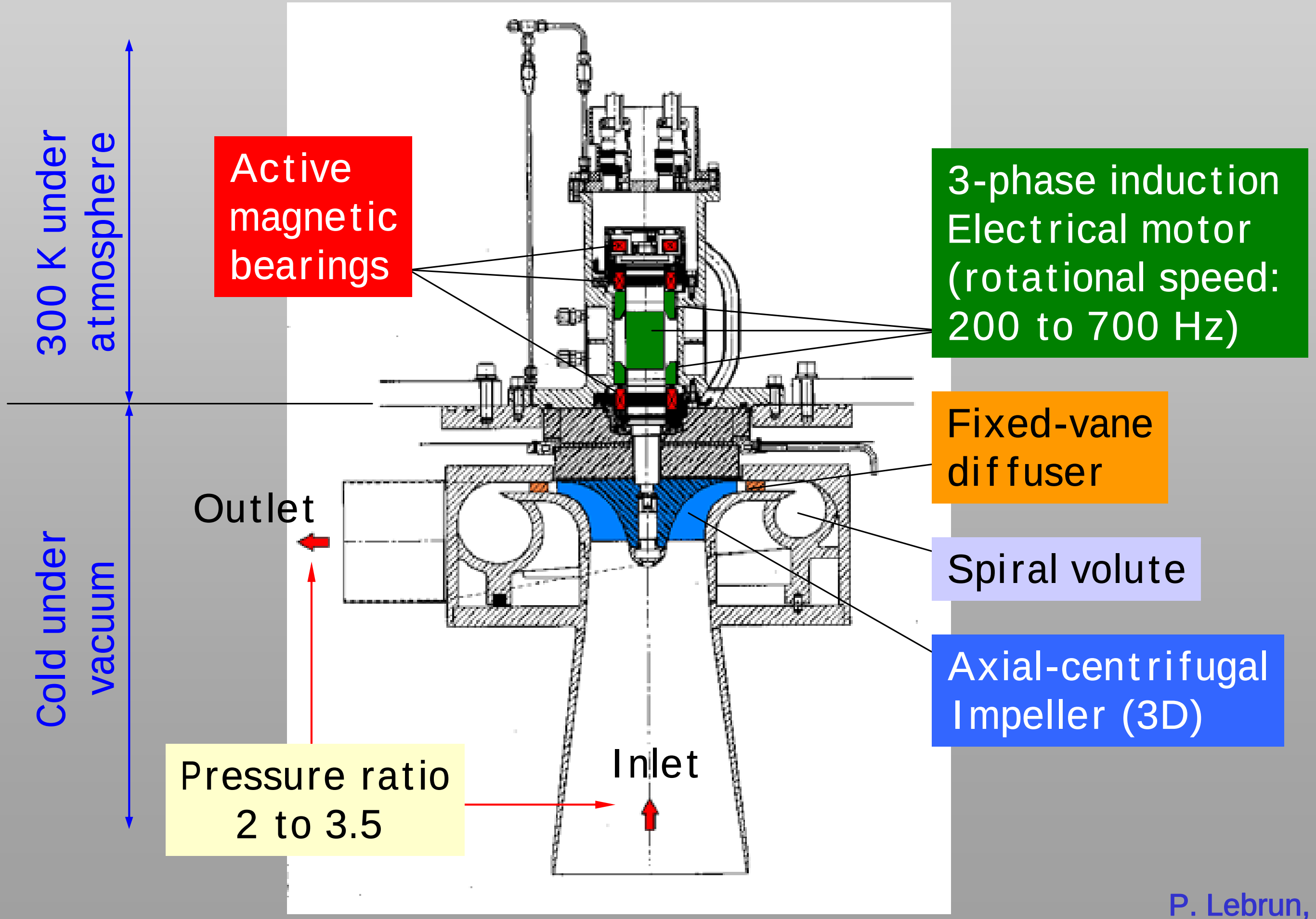


P. Lebrun, CERN

Users demanded refrigerators with sub-atmospheric helium saturation pressure: One has the choice between warm and cold compression of the low pressure helium gas.



Main Features of LHC Cold Compressors



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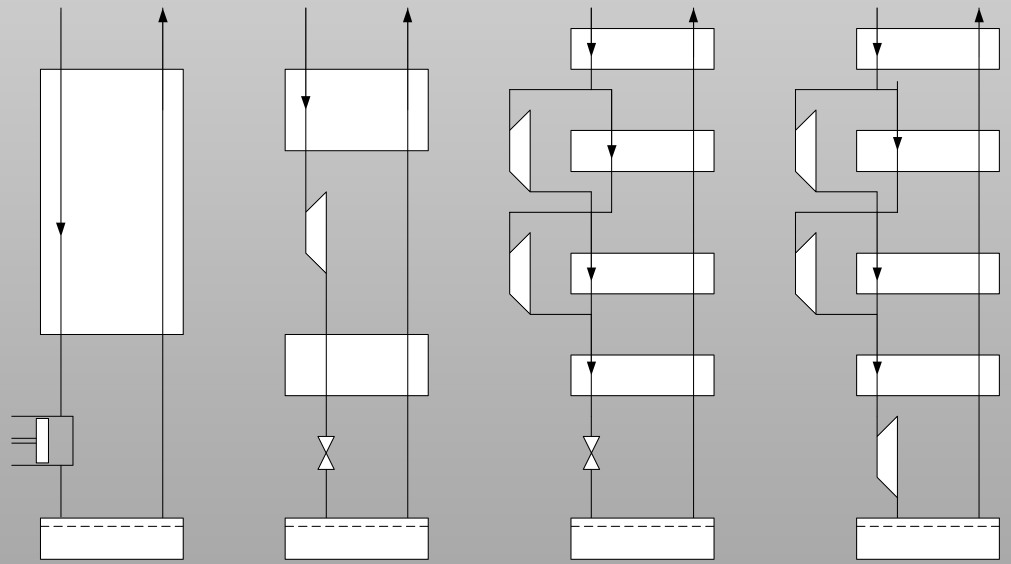
Low cost or high efficiency?

In most fields of technology you have to pay a higher price to get a system with lower energy consumption.

But not with large cryogenic refrigerators!

Development of the JT region of large helium refrigerators



	Joule-Thomson	Wet Expander Collins (ca. 1965)	JT - Turbine FNAL 1975	Double JT - Turbine DESY HERA 1985	Triple JT -Turbine CERN LEP 1990
Efficiency (%)	18	23	23	28	30
COP (W_{el}/W_{refr})	370	290	290	240	224

The helium refrigerator paradox:

Increase the number of expanders!

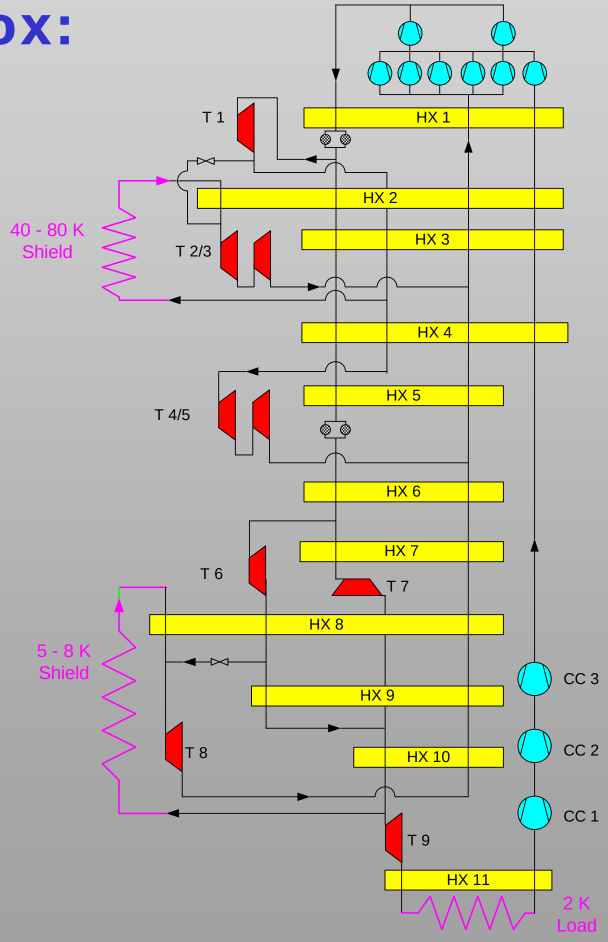
This increases of the efficiency of the cycle.

<u>This reduces the power consumption</u>

This also reduces the cycle mass flow rate.

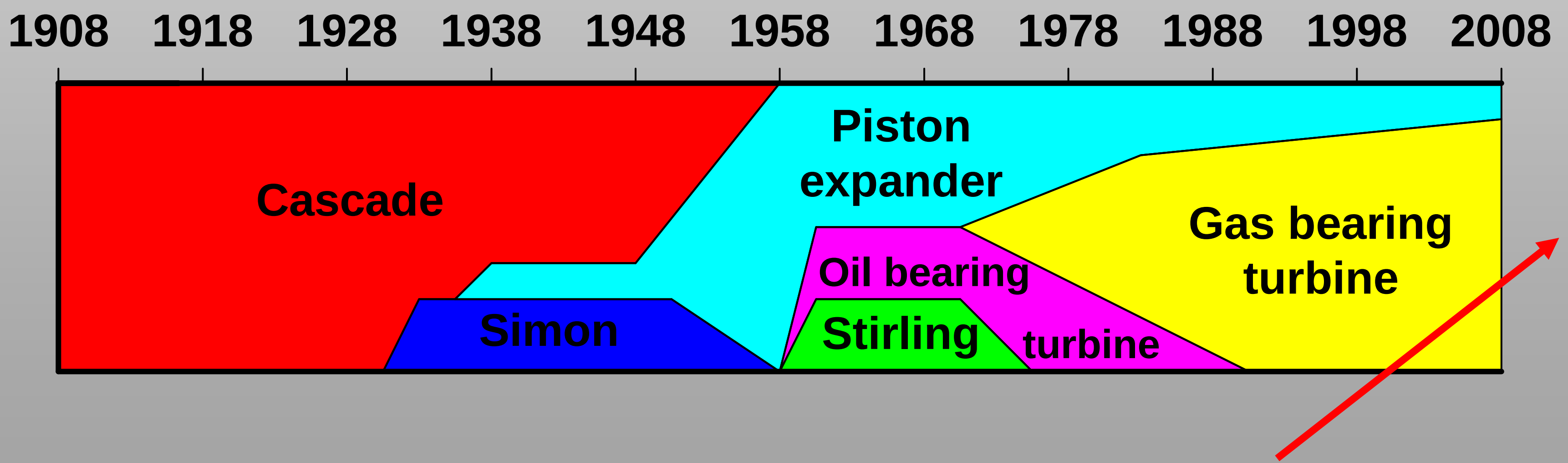
This reduce the number of compressors.

<u>This reduces the initial cost of the plant!</u>



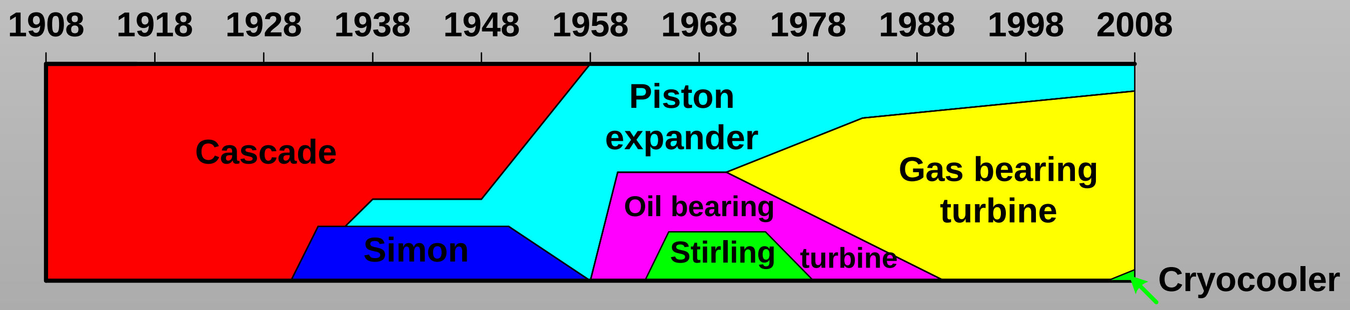
Result: With many turbines one gets a cheaper plant plus lower power consumption!

Helium liquefaction: What will the future bring ?



There is still room for further inventions !

Cryocooler based helium liquefiers



Picture: Cryomech