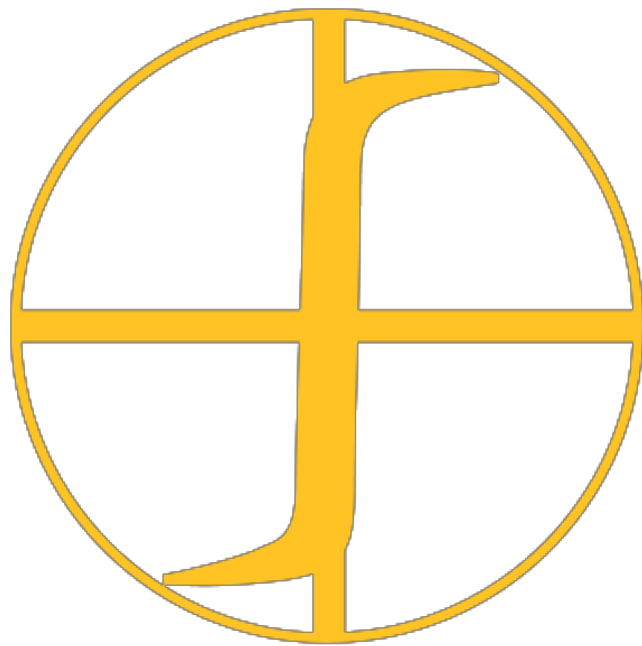




Advanced Induction Materials and Technology



O n l i n e I n d u c t i o n H e a t i n g C o u r s e

7. Case Stories

by. Dr. Valentin Nemkov

Historical Overview of Induction Melting and Heating

Alfred Mühlbauer

Hannover

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- Fundamental Principles
- Application of Electromagnetic Induction
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 - Power Sources
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- Conclusions

➤ Fundamental Principles

Fundamental Principles: The Pioneers



1831

Michael FARADAY (1791-1867) discovered that if a magnet was being approached to an electric circuit, while the magnet was moving, in the circuit was produced a temporary induced current. Even when the magnet was removed, another temporary current was produced, with an opposite direction:

The principle of electromagnetic induction was born



1864-73

James Clerk MAXWELL (1831-1879) has developed his genial theory of electromagnetism based on the electric and magnetic phenomena discovered by Oersted, Faraday, Ampere and Ohm. It was introduced in the treatise „**Electricity and magnetism**“, creating the unified theory of electric and magnetic phenomena with his well known equations.

Fundamental Principles: The Pioneers



- 1840** James Prescott JOULE (1818-1889) formulated in the course of his investigations of the heat emitted in an electric circuit the law of electric heating in 1840, known as **Joules law**. It states that the amount of heat produces in a conductor by an electric current each second is proportional to the resistance of the conductor and to the square of the current. Joule experimentally verified the **law of energy conservation** in his study of the transfer of mechanical into thermal energy.



- 1866** Werner SIEMENS (1816-1892) discovered the **dynamo-electrical principle**.
- 1867** He built the first already technically usable dynamo machine. The basis for a quickly developing electrical engineerig was created.

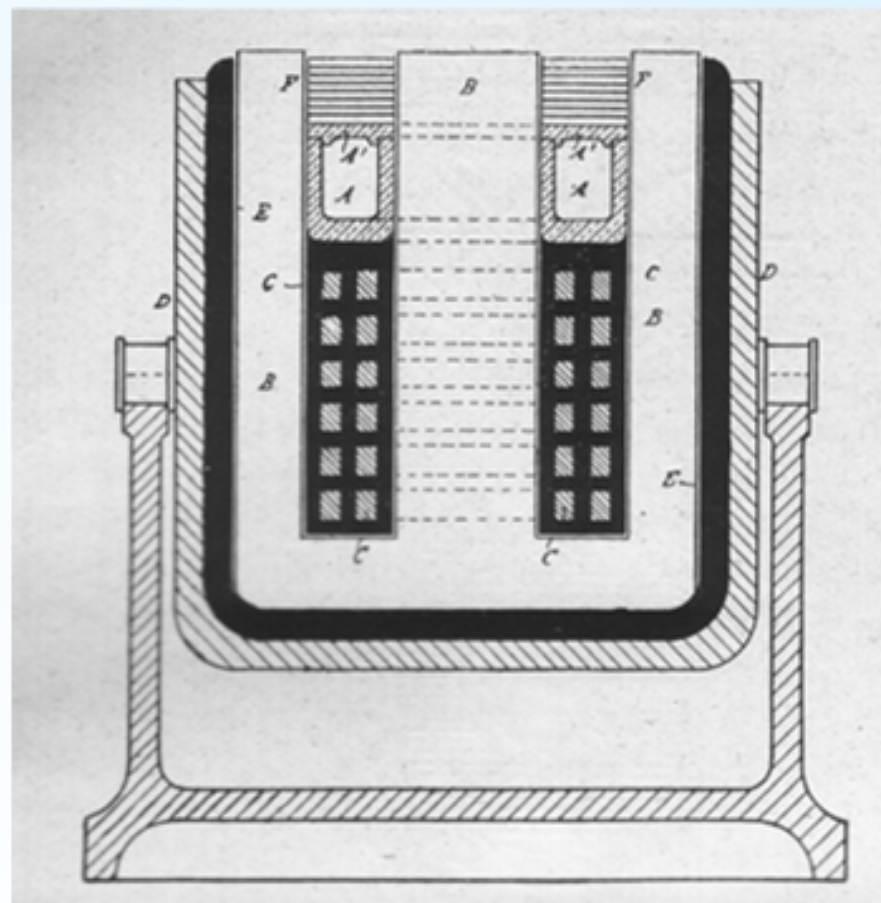


- Fundamental Principles
 - Application of Electromagnetic Induction
- ## Induction Melting

Development of Induction Melting



S. Z. de Ferranti

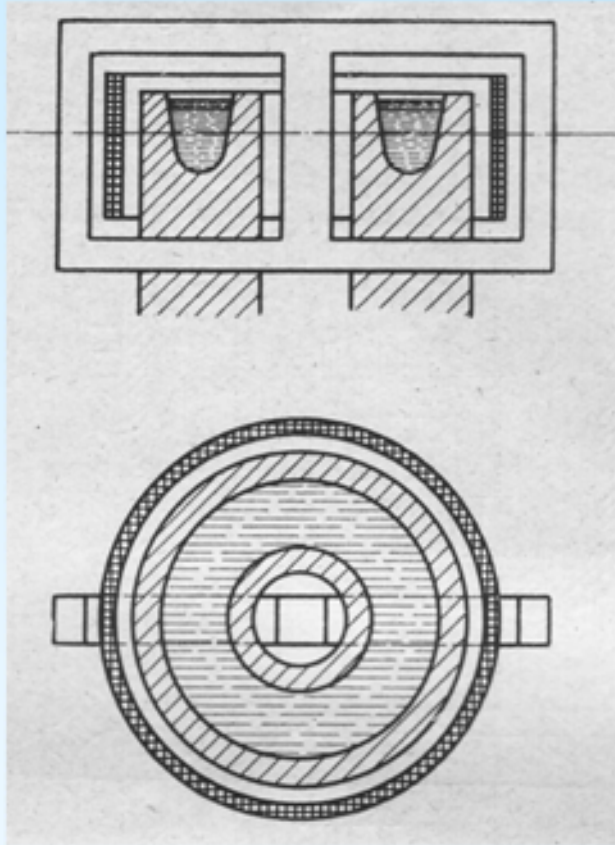


1887 Sebastian Z. de Ferranti, U K, proposed the application of induction currents in a transformer for the melting of steel.

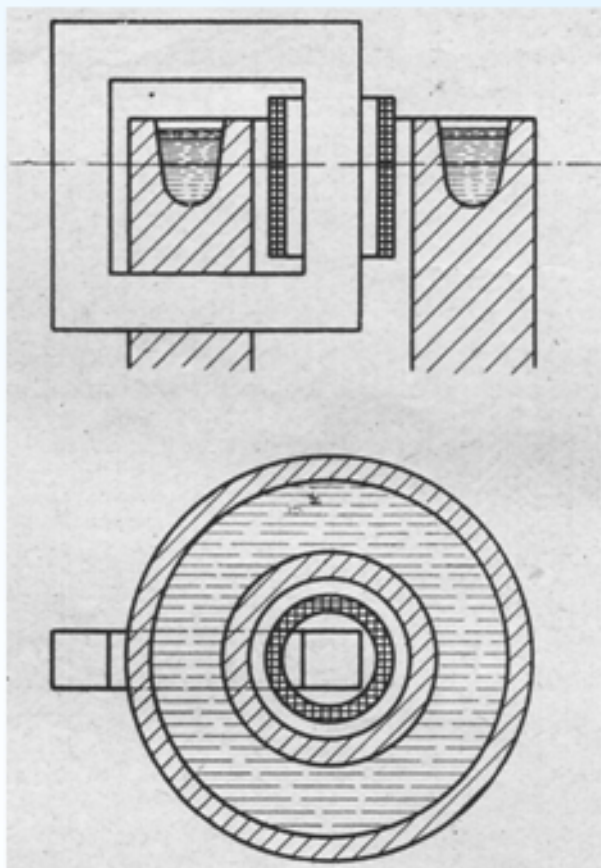
He described the **first** induction furnace by the English patent no. 700.

Ferranti was able to heat metal in the ring-shaped channel of his furnace (left), and if he used a metallic container it was possible to heat up water.

Development of Induction Melting

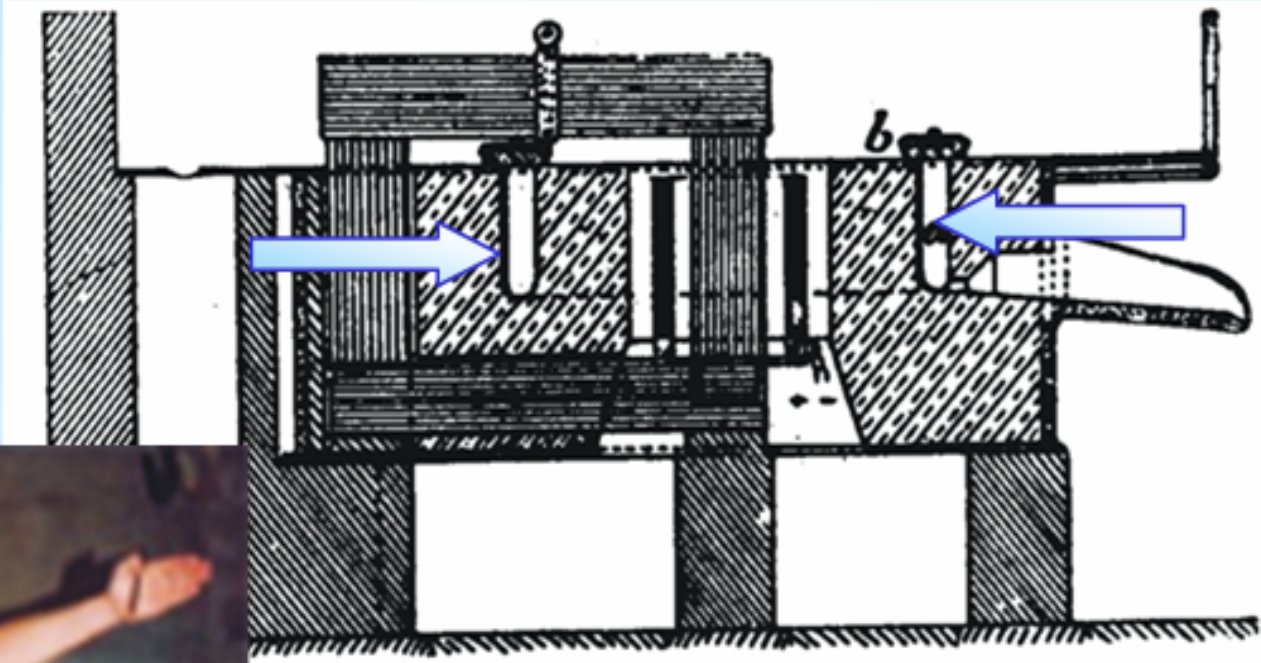


1890 Edward A. Colby, USA, has tried to use electromagnetic fields for the heating of metals, but because of the low frequency and, hence, low power density in the charge his experiments were not successful



1891 F. A. Kjellin, Sweden, presented the **first** useful mains frequency induction furnace for the melting of steel.

Development of Induction Melting



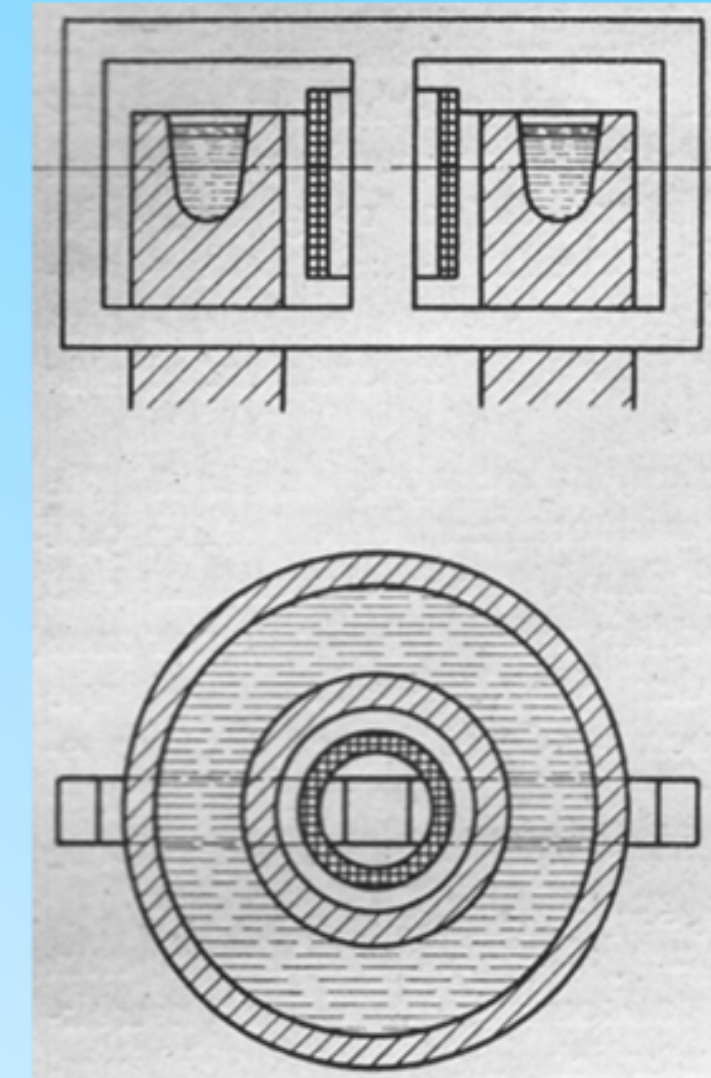
1900 This furnace was set into operation at Benedicts Bultfabrik in Gysinge, Sweden. The open channel acted as a single secondary winding.



F. A. Kjellin

1905 Second Kjellin furnace with double magnetic yoke, installed in Völklingen, Germany.

1905 Schneider-Creusot, France, obtained a French patent no. 361 627 for a HF furnace.



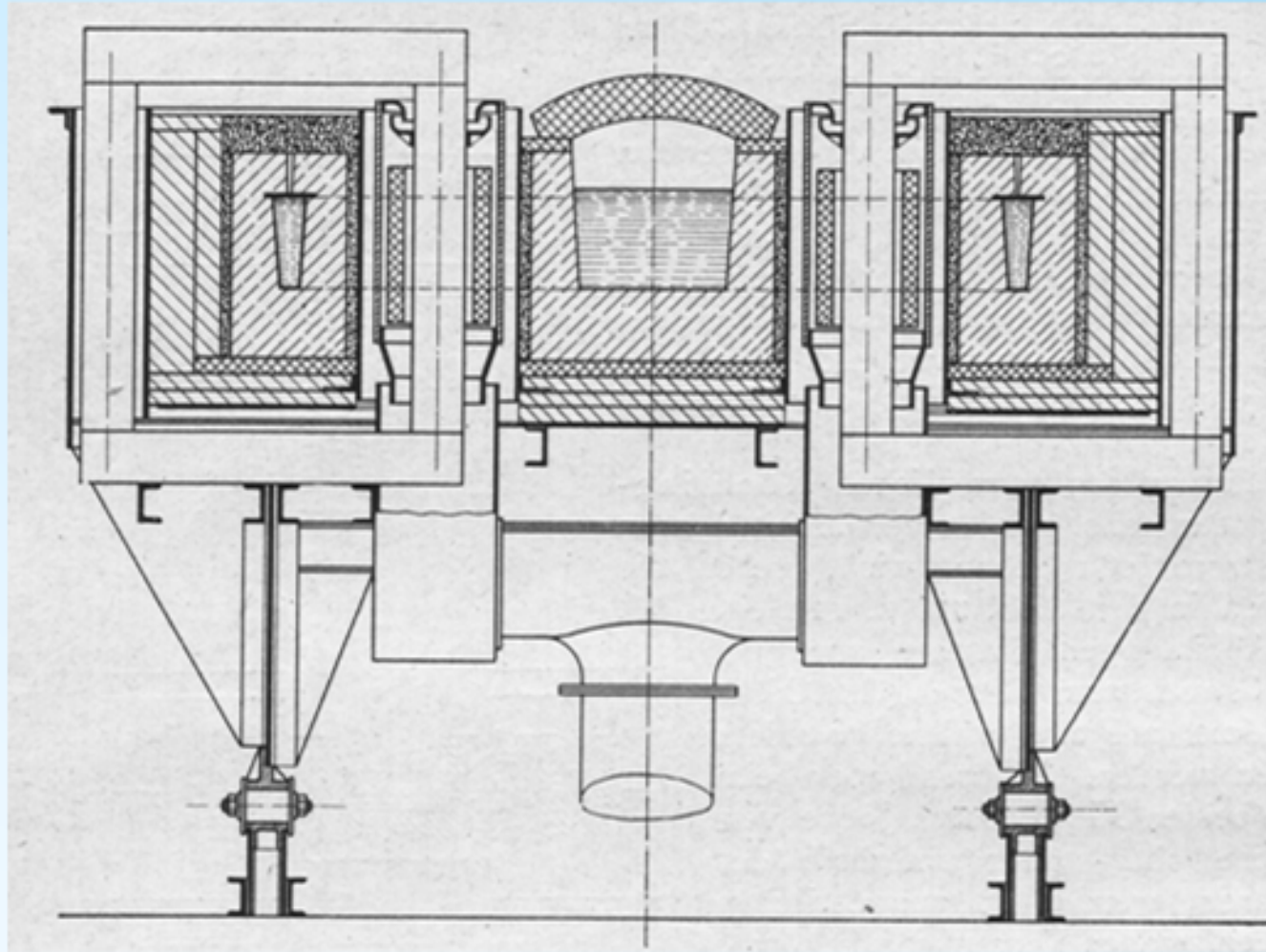
Development of Induction Melting



Edwin F. Northrup

- 1907** Edwin F. Northrup and Carl Hering investigated in USA electromagnetic stirring forces- pinch effects- in the melt of induction furnaces.
- 1916** E. F. Northrup designed the **first** high frequency furnace in the Palmer laboratory at Princeton.
Many have heard the nice story how the first patent for this furnace was granted.
Edward F. Northrup was, without any doubt, one of the outstanding scientists in the field of induction melting and heating.

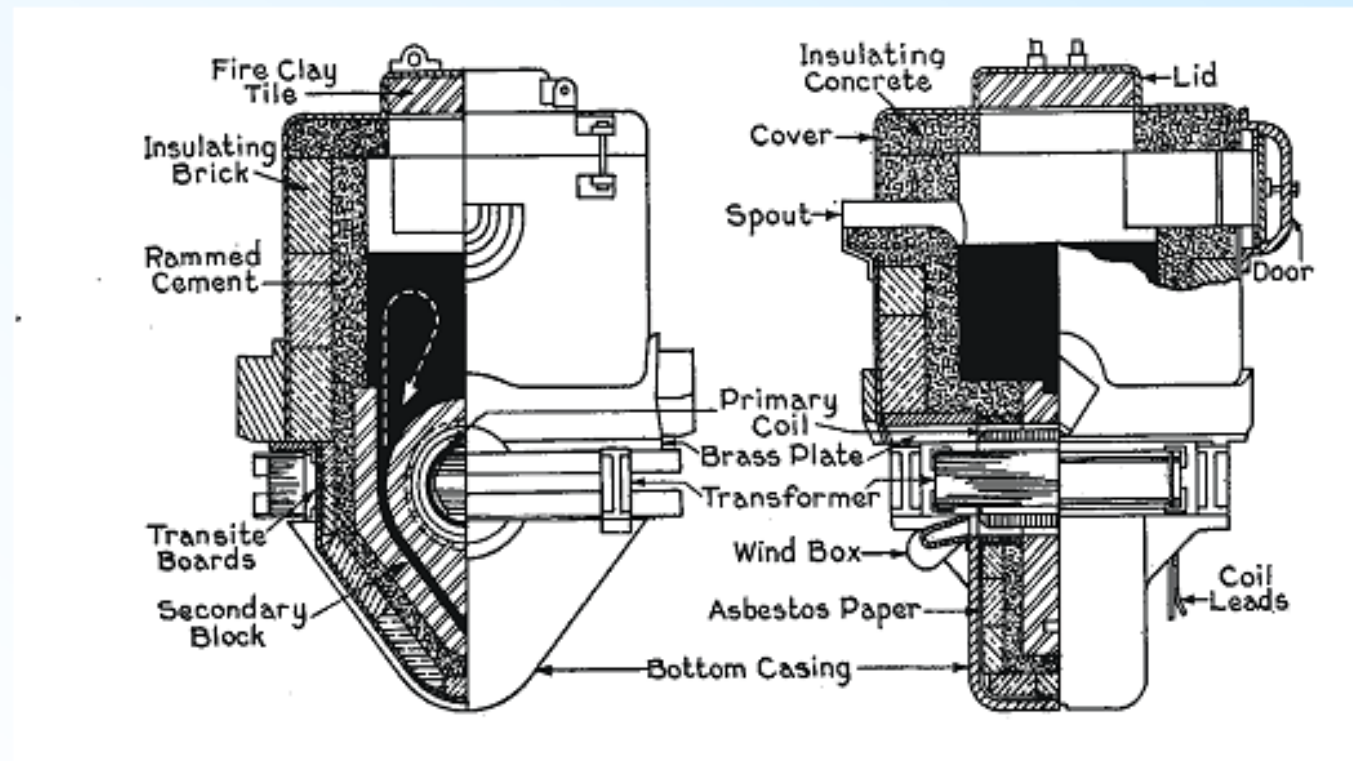
Development of Induction Melting



1913 Röchlin-Rodenhauser, Germany, presented an induction furnace with two closed horizontal channels heated a central working hearth.

1916 Ajax Electric Furnace Company (USA) realized the mains frequency channel furnaces with closed, vertical branches for the melting of copper alloys.

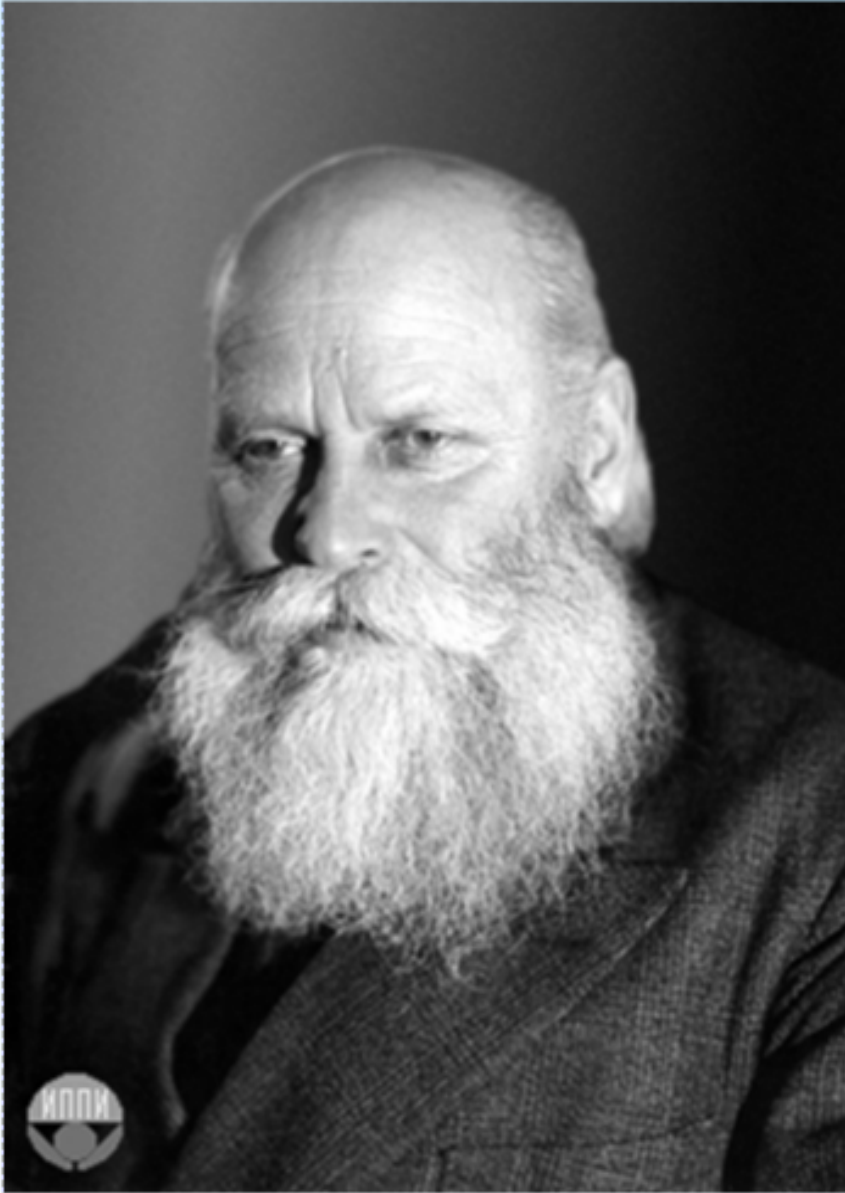
1917 E. F. Northrup obtained a patent on the determination of the relation between skin depth and frequency for the high frequency induction furnaces.



Development of Induction Melting

- 1920** E. F. Northrup built a prototype of a vacuum induction furnace.
- 1920** M. G. Ribaud, France, started independently from Northrup the development of HF furnaces. For his melting experiments he employed a rotating spark-gap generator with frequencies from 50 kHz to 100 kHz.
- 1922** The Kaiser-Wilhelm-Institut für Eisenforschung, Germany, realized a medium frequency furnace, supplied by a motor generator instead of the unstable and uneconomical spark-gap generator.
- 1923** The process of melting metals under vacuum was a great technological innovation. The development of the induction vacuum melting technology by Wilhelm Rohn, led to the foundation of the *Heraeus* vacuum melting facility.

Development of Induction Melting



Valentin P. Vologdin

- 1922** Valentin P. Vologdin presented and put into operation machine generators of 50 kW and 15 kHz. Since 1912, he had developed and built HF machine generators for radio applications. In the 20s a 150 kW and 15 kHz generator was installed in the Moscow transmitting station for a stable radio contact of Russia with countries of Western Europe and USA.
- 1926** V. P. Vologdin started investigations about the industrial use of high frequency currents and soon after he had already developed coreless induction furnaces for the melting of ferrous and non-ferrous metals, supplied by machine generators. Some years later he has used HF tube generators instead of machine generators.

- Fundamental Principles
 - Application of Electromagnetic Induction
Induction Melting
- ## Power Sources

Development of Power Sources

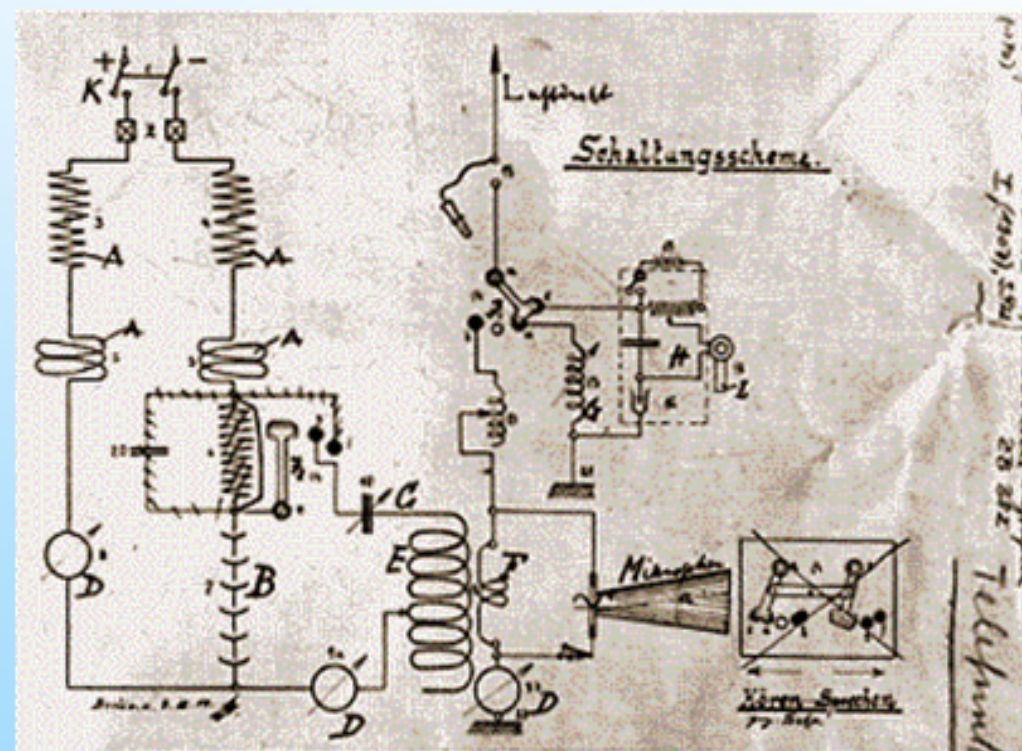
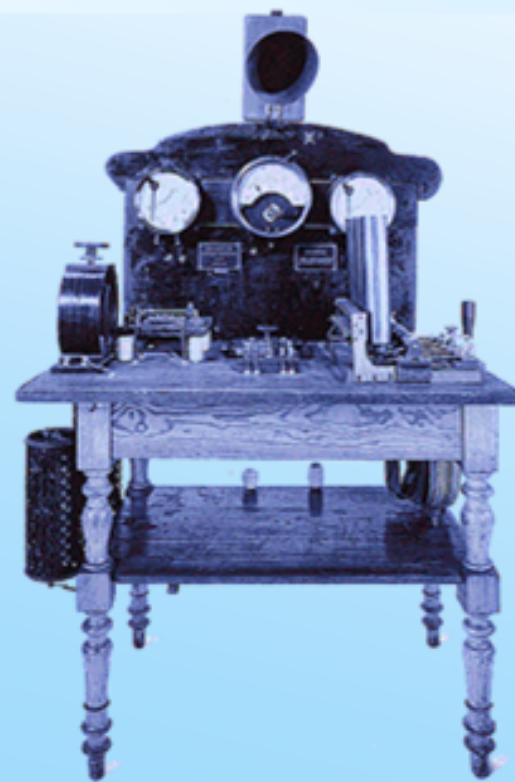


E. Alexanderson

At the beginning, the activities was concentrated on the development of HF power sources for radio purposes. The power output was small and the energy costs high.

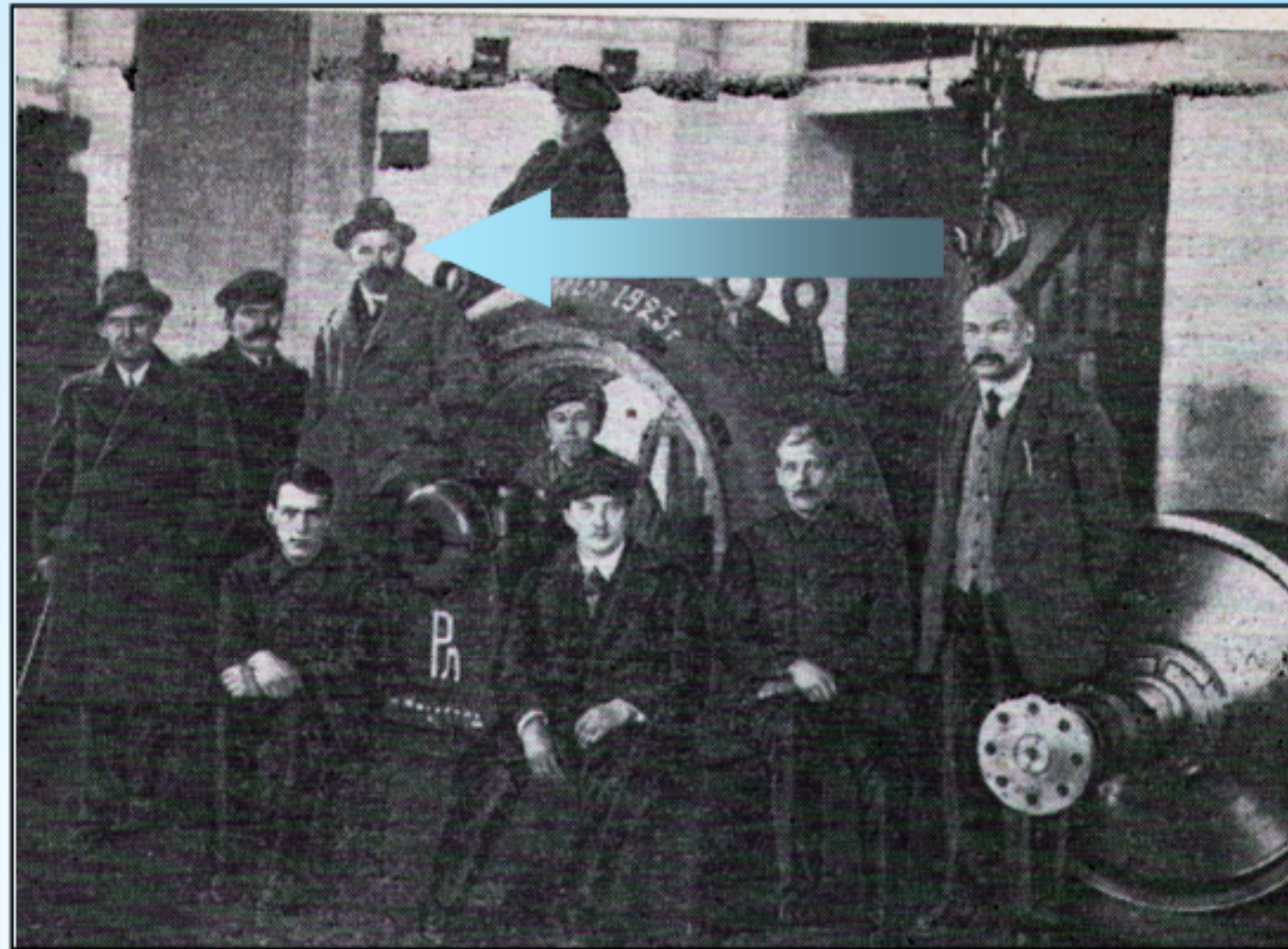
1903 Valdemar Poulsen developed at Lorenz Company, Germany, the **first** arc- transmitter for radio communication, see below.

1906 Ernest Alexanderson, USA, presented the **first** larger HF-machine generator for 50 kHz at General Electric.



At the same time, in USA an other technology was developed to create un-damped oscillations for radio applications.

Development of Power Sources



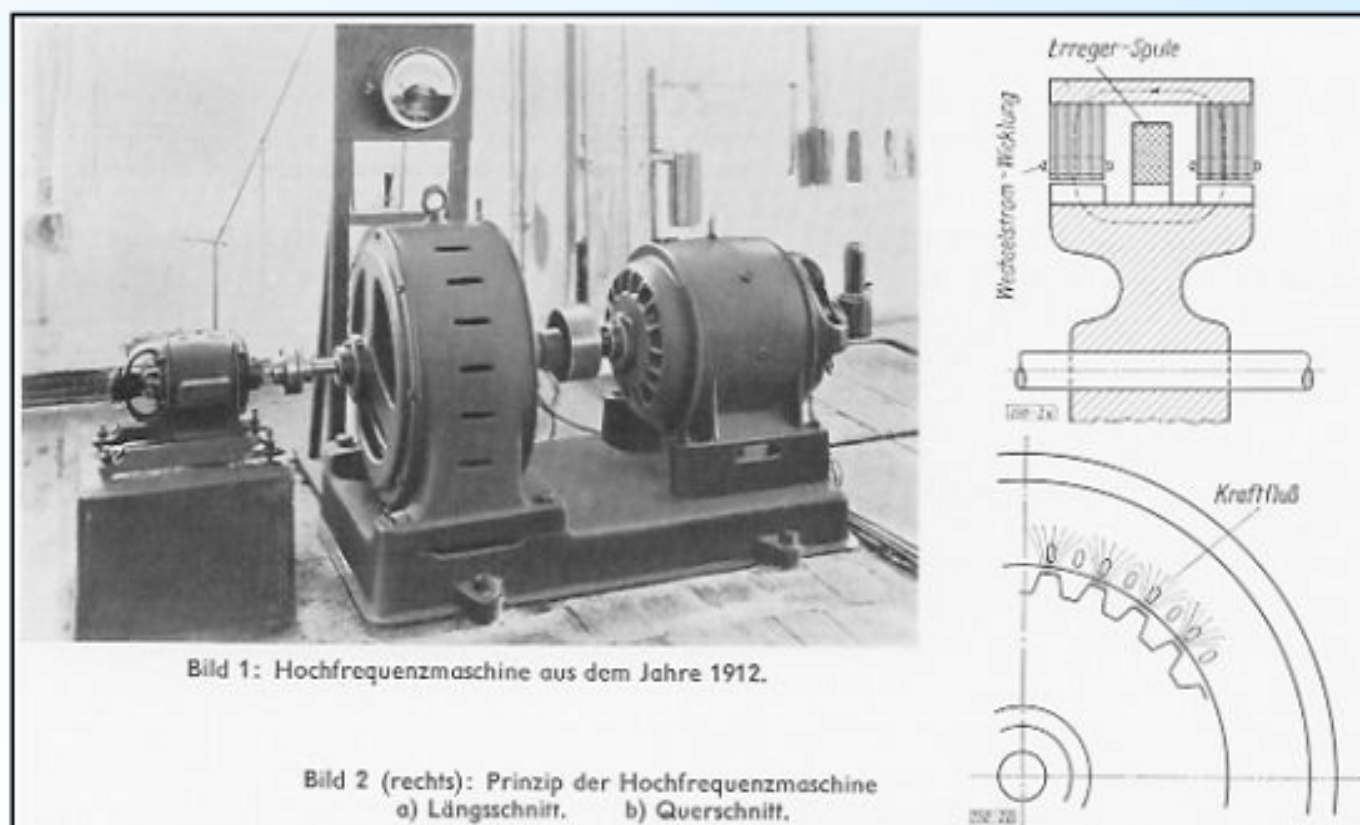
1912 Valentin P. Vologdin developed in Russia machine generators for radio applications.

1912 Telefunken, Germany, presented a HF-machine generator of 2 kW (see below).

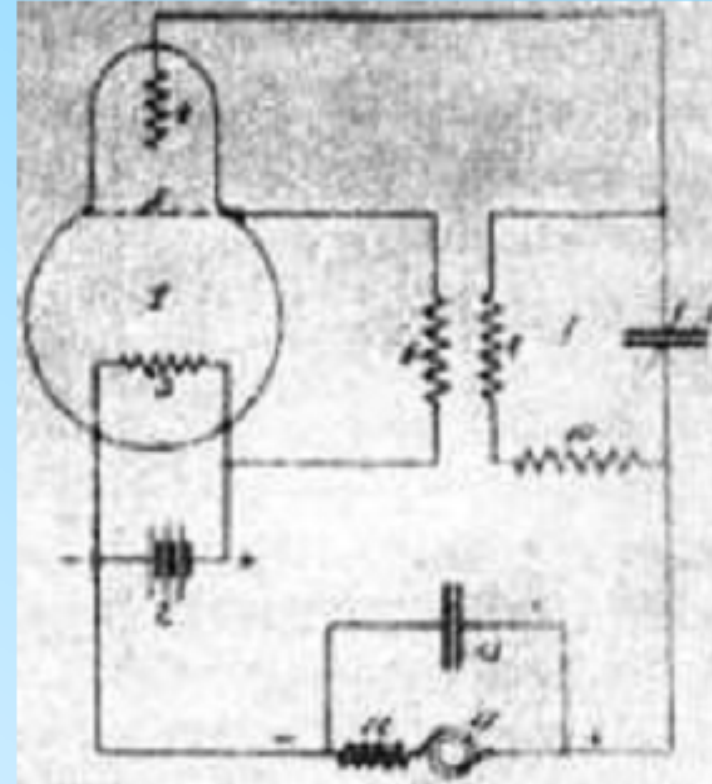
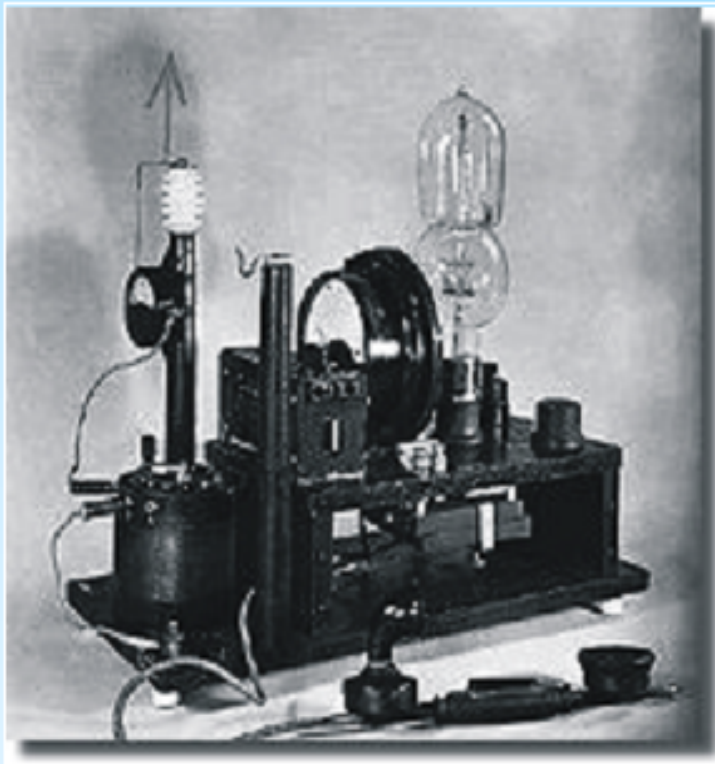
1923 V. P. Vologdin put at first a large HF- machine generator of 50 kW, 20 kHz into operation.

1926 He made **first** use of a HF-machine generator for induction.

1930 V. P. Vologdin has used a 30 kW, 200 kHz HF- tube generator for induction melting.

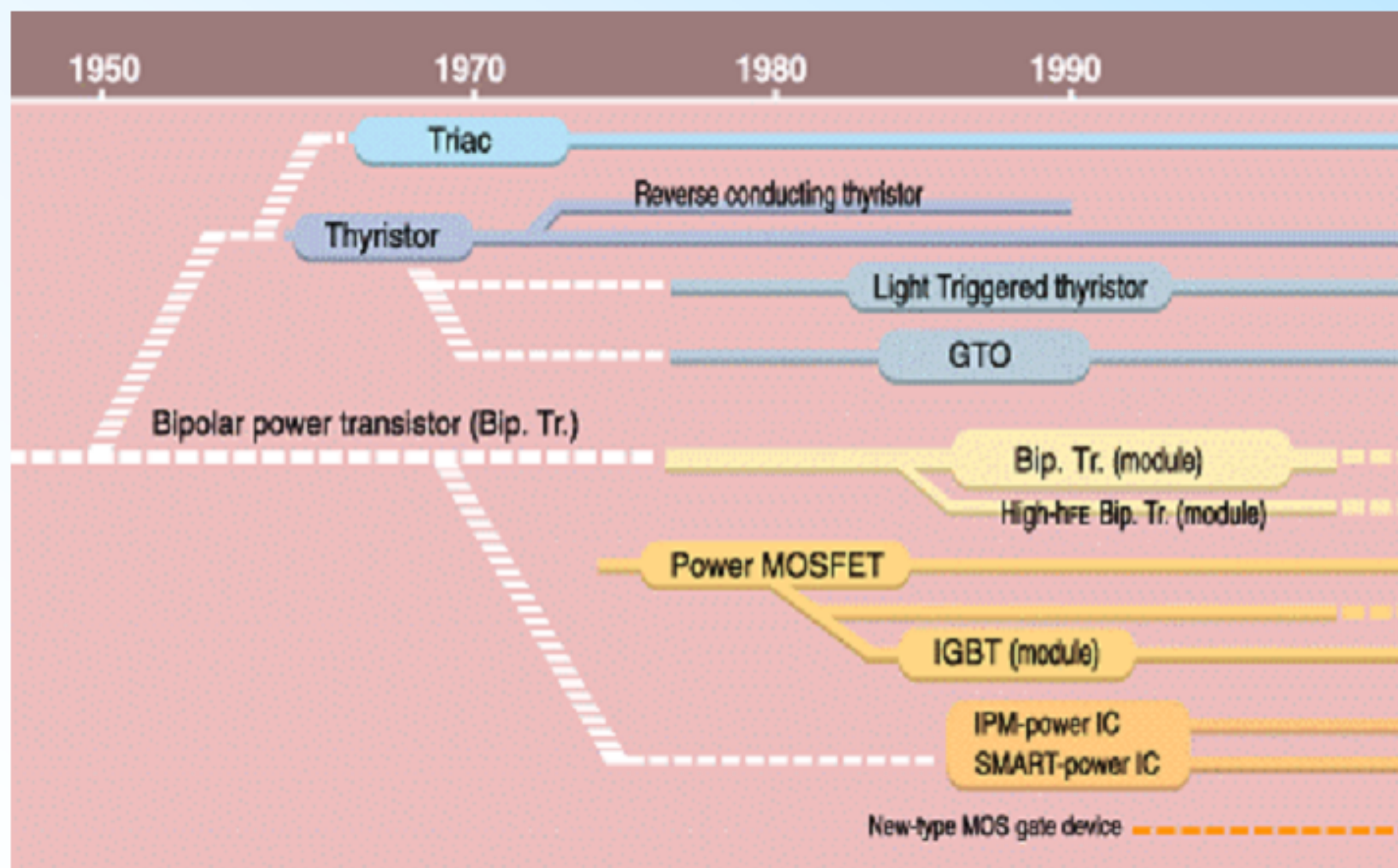


Development of Power Sources



1913 Alexander Meißner presented and patented the **first** tube generator with a feed-back circuit (left) for radio applications at Telefunken.

1925 During a business trip to Russia, he ordered the first powerful transmitting tube of 25 kW at the Leningrad Company Aibas.



The further development of power sources for induction heating is closely connected with the development of power electronic devices.

- Fundamental Principles
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Induction Melting: Continuation

Development of Induction Melting

- 1925** One of the first European high frequency melting plants, supplied by a rotating machine generator, was put into operation at the Kaiser-Wilhelm-Institut (KWI) for iron research at Düsseldorf, Germany. For iron charges of up to 30 kg, frequencies in the range of 5 kHz were used.
- 1926** Franz Wever and Wilhelm Fischer, KWI, published the results of their extensive investigations about the electrical behaviour of core-less HF melting furnaces. They showed a complete theory on this kind of furnaces. The calculation results were experimentally tested and their limits demonstrated.
- 1927** The Electric Furnace Corp. had installed the first HF furnace at Sheffield and since then, a steadily growth of number of induction furnaces and their size took place in England.

Development of Induction Melting

- 1931** Wilhelm Esmarch, Germany, presented a complete theory for real sized induction crucible furnaces that determine the practical calculation in industry. His method yielded accurate results, which agreed well with measurements, obtained at installations of industrial scale.
- 1931** Siemens & Halske took the **first** patent for the ceramic free induction melting in water cooled crucibles as DRP 518.499, an actual technology important for the manufacture of TiAl motor valves and turbine blades, etc.
- 1933** At the *electro heat exhibition* in Essen, Siemens & Halske presented a 4 t-crucible furnace. Several other 4 t-crucible furnaces were put into operation in 1934 in various companies in Germany and in Sweden.
- 1933** In Sweden, ASEA developed dual frequency furnaces whose melting period ran with 500 Hz to 1,000 Hz and their stirring action with 50 Hz.
- In Russia 9 HF furnaces with a volume of 6 t and a total power of 2,450 kW are already in operation.

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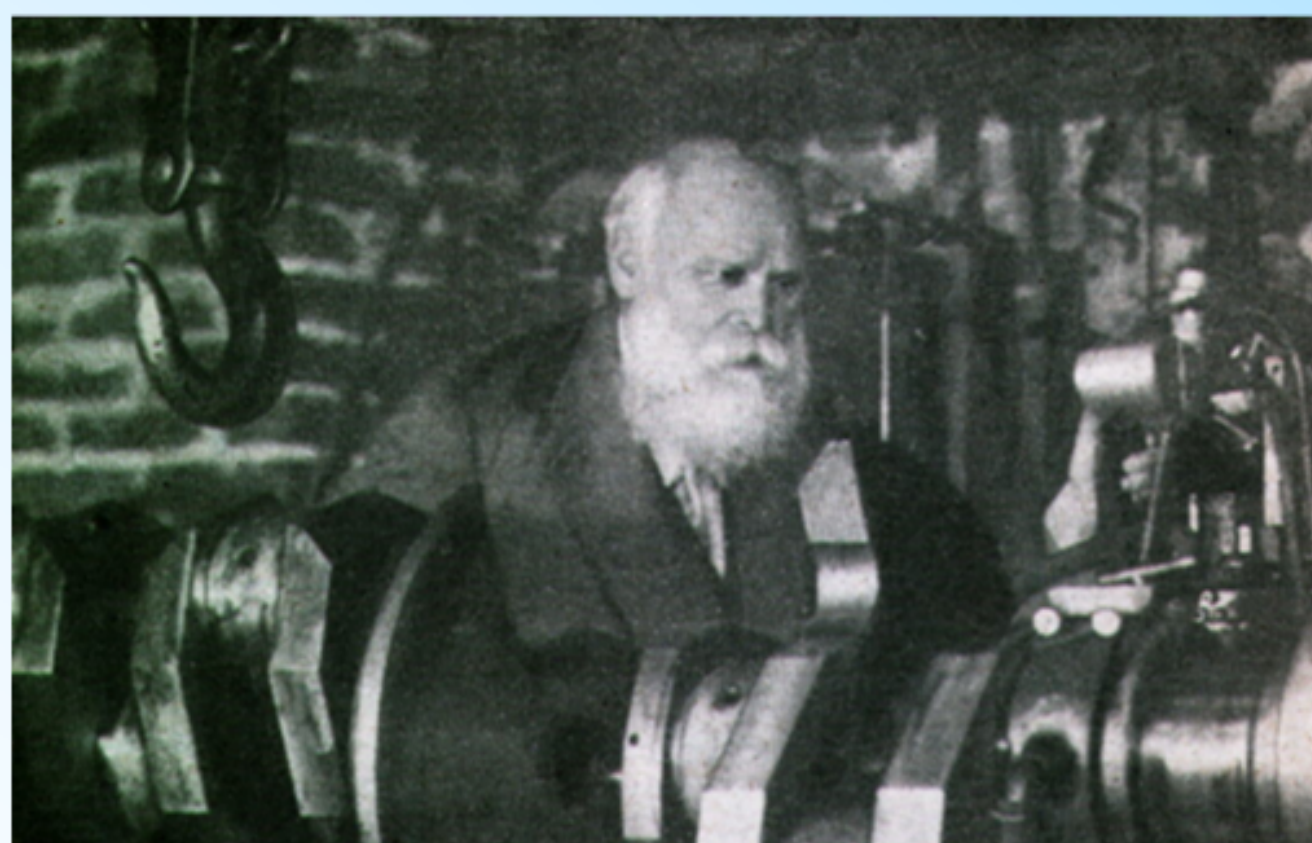
Development of Induction Heating

- The development of powerful car and aircraft engines gave new impulses.
- The material strength were not sufficiently high for those applications, while the mechanical strain increases strongly.
- To decrease the wear, one began to harden the surfaces were exposed to abrasion.
- Well known methods for partial hardening were not efficient enough, therefore more accurate methods were required:

The development of induction hardening was started.

Development of Induction Heating

On the suggestion of the Moscow automotive industry, V. P. Vologdin successfully continued his investigation and development of the HF surface hardening of steel parts, including crankshafts.



V. P. Vologdin in the hardening department
(1940)

Therefore, **V. P. Vologdin** can be designated as the **inventor** and **promotor** of the modern surface hardening technology.

1935 He got the **first** patent in this area.

1939 He published the results of his theoretical and practical experiences with the high frequency induction surface hardening in the Russian monograph "Surface hardening by induction technique".

In this early and basic treatise not only the theory of HF surface hardening was considered, but also the temperature distribution in the parts while heated, examples of different hardening tasks and some calculation examples.

Induction Melting and Heating State of the Art in the Middle of the 30s

- The theoretical frame of electromagnetic induction melting and heating as well as many practical experiences were available and together formed a complete set of knowledge.
- Many R&D groups around the globe were engaged in this field.
- The development of induction melting and heating was closely connected with the development of power sources.
- **Mainly two outstanding individuals have shaped the development
Dr. Edwin F. Northrup in USA and
Prof. Valentin P. Vologdin in Russia.**
- The technical preconditions for a wide initiation of induction heating into the metalworking industry were fulfilled as well.

Development of Induction Heating

Further developments during the World War II showed very clearly the advantages of induction heating, including the very accurately adjustment of heated depth and surface areas. No contact between coil and work piece was necessary and high power densities with short heating-up times were readily available.

Before **1940** Siemens & Halske erected in Germany a plant for hardening of armour plates: 1,800 kW MF-power. In **1942**, the Deutsche Edelstahlwerke established the *Elotherm Company* with the aim, to produce induction heating installations for surface hardening, through heating, soldering and special domains. **1943**, Elotherm delivered two industrial scale induction hardening plants of 750 kW power.

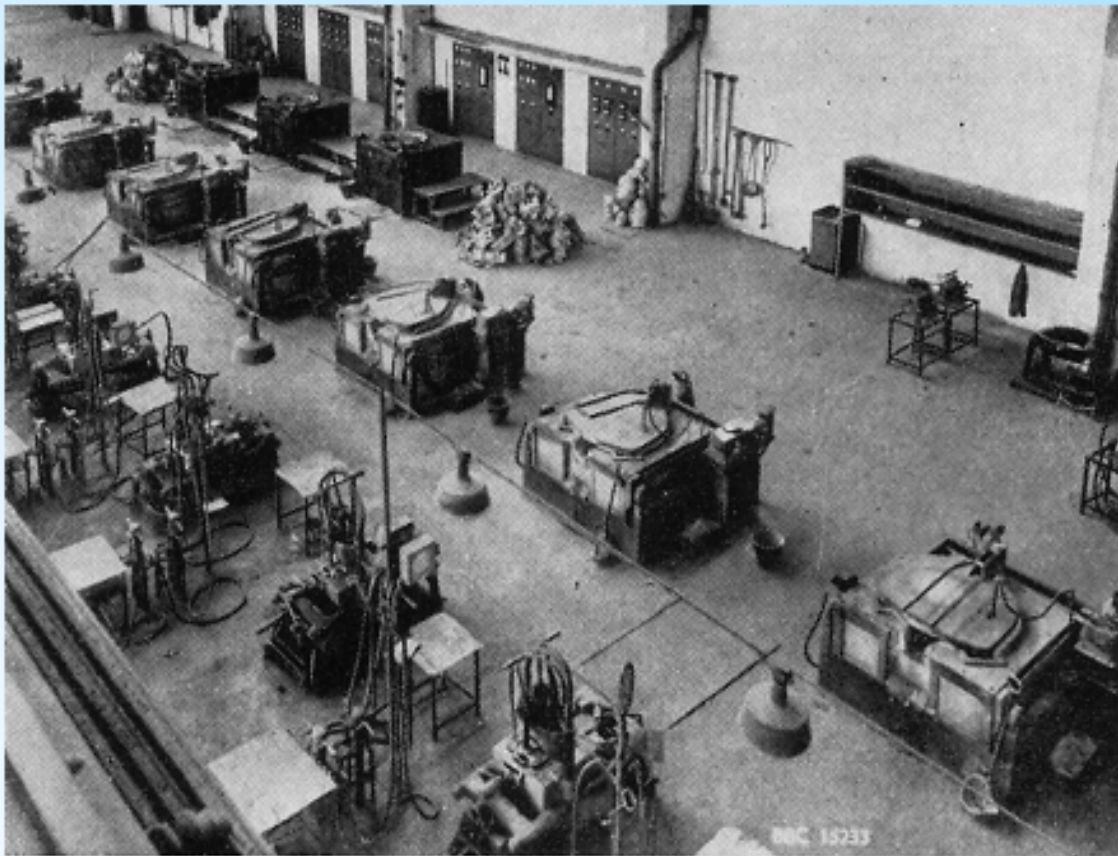
In the USA E. F. Northrup continued his investigation of induction heating for thermal metal treatment. He published several related articles. The **Ohio Crankshaft Corp.**(Tocco) reported on surface hardening in 1936, especially on selective hardening of crankshafts and started mass hardening of crankshafts.

Many other investigations on surface and through heating by induction were carried out at various countries.

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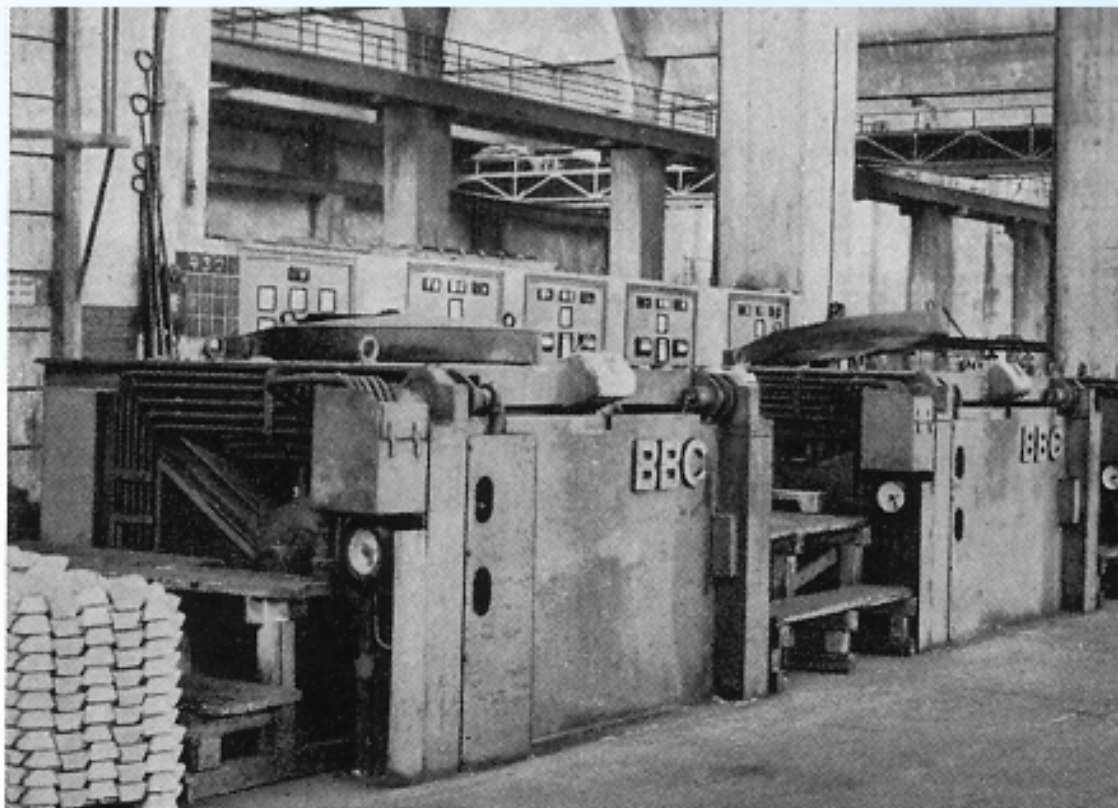
Induction Melting: After 1945

Development of Induction Melting: After 1945



In the **50s**, all-electric foundries for the melting of ferrous and non-ferrous metals were already in operation. Such an all-electric foundry plant was equipped by Brown, Boveri & Cie. with:

- 23 Line frequency crucible furnaces for Mg melting, each 450 kW and 600 kg
- 8 Line frequency crucible furnaces for Al melting, each 360 kW and 1.3 t,
- 3 Line frequency channel furnaces for grey iron melting, each 500 kW and 8 t,
- 3 Arc furnaces, each 8 t,
- 140 Resistance heated holding furnaces, in total 25 MW.



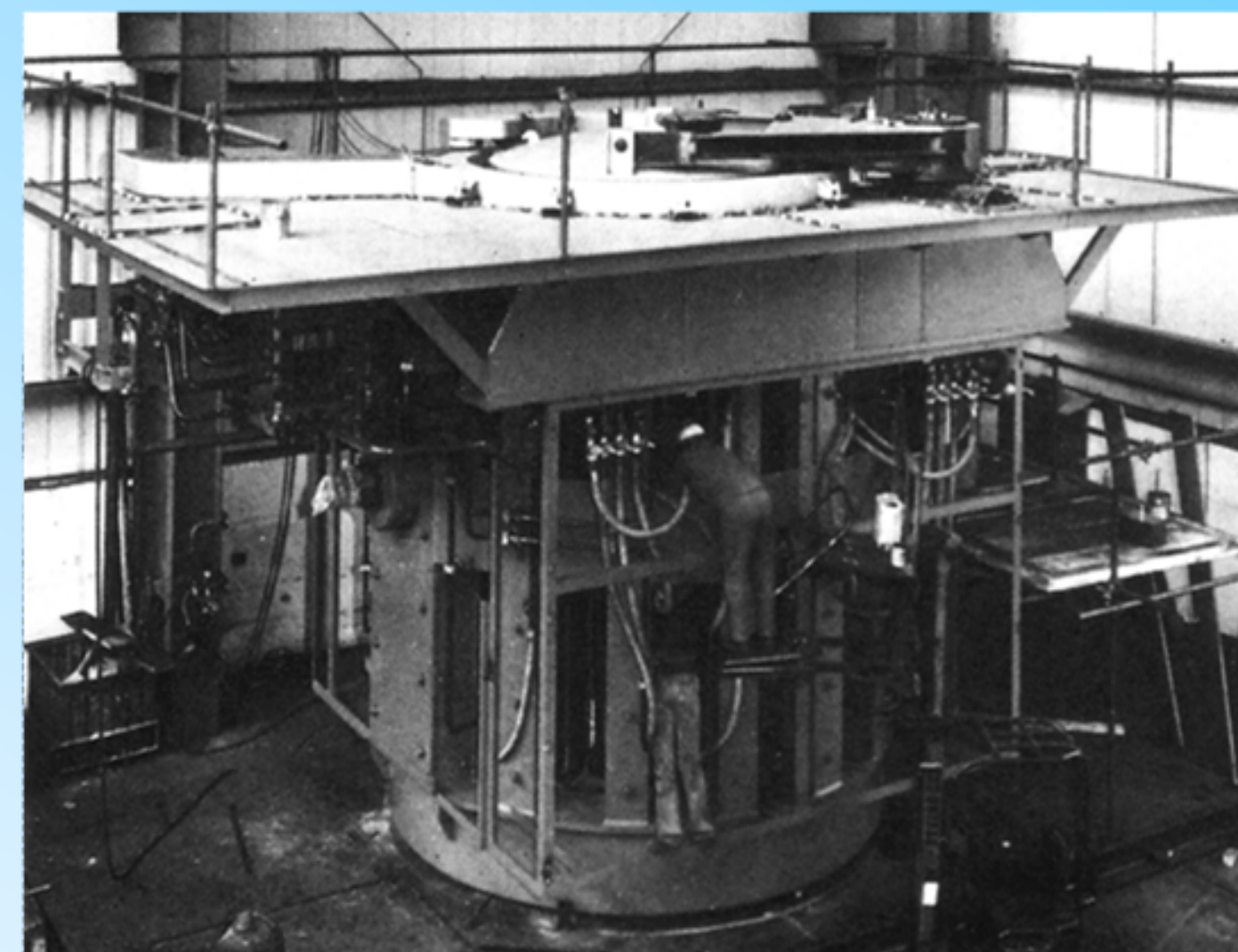
Development of Induction Melting: After 1945

In the years after **1950**, the implementation of powerful induction melting equipment was characterized by a step-by-step increase of furnace capacities, power densities and production rates.

In the **60s**, the booming automobile industry needed an extremely high amount of iron. The consequence was that the large foundries had to extend their capacities remarkably. This yields to the construction of large induction furnaces.

1964 Brown, Boveri & Cie. developed and put into operation in USA (1967) the largest and most powerful induction crucible furnace of the world for grey iron melting:

Data:	Furnace capacity	60 t
	Rated power	21,000 kW
	Frequency	60 Hz
	Melting rate	40 t/h
	Power density	350 kW/t
		<i>world's record</i>



Development of Induction Melting: After 1945

1977 Brown, Boveri & Cie. put into operation a **first** turn key steel plant, consisting of two 30 t- furnaces with 8,000 kVA power, including all necessary accessory parts like pre-heater, transport equipment and others.

In those years **solid state MF converters** replaced the machine generators, because solid state devices like thyristors became less expensive.

The new excellently controllable thyristor converters enabled the experts to realize medium frequencies according to the technological requirements.

For larger crucible induction furnaces, frequencies of about **250 Hz** were common. For smaller furnaces, the chosen values were somewhat higher.

Development of Induction Melting: After 1945

In the **80s** the so-called high-performance crucible furnaces were introduced.

The increase of frequencies, e.g. from 50 Hz to 250 Hz, the installed power density could be increased by a factor of

$$(250 \text{ Hz} / 50 \text{ Hz})^{0,5} \approx 2.24$$

keeping the melt motion at the same level as for a 50 Hz furnace. The power density is than

$$2.24 \times 350 \text{ kW/t} = 784 \text{ kW/t.}$$

A closer investigation of the relationship between melt motion and frequency to a possible power density for cast iron of about

1,000 kW/t

Development of Induction Melting: After 1945

Such induction crucible furnaces can be built smaller. The higher power density allows a fast melting. The smaller capacity corresponds to higher flexibility.

Brown, Boveri & Cie. built end of the 80ies two high-power crucible furnaces for grey iron, one 6 t / 6 MW, the other 12 t / 9.3 MW and both with 250 Hz.

The operation of such high performance furnaces, characterized by a very high power density of up to **1,000 kW/t**, which is three times higher as before, requires a very careful and precise process control.

That is why the development of a complex electronic process control system for melting and pouring operations was an absolutely necessary prerequisite, in order to ran it reliable.



Development of Induction Melting: After 1945

The today's state of the art of induction melting is characterized by furnaces such as:

- **High performance, flexible crucible furnaces with high power densities,**
- **Large furnaces for mass production:**
 - 20 t and 16,000 kW, i.e. 800 kW/t, at 250 Hz for cast iron melting in crucible furnaces,
 - 75 t and 16,000 kW at 250 Hz for brass melting in a crucible furnace,
 - 18 t and 2,400 kW at 50 Hz, 9 t/h, for copper melting in a double-loop channel furnace,
 - 60 t and 1,500 kW at 50 Hz for aluminium melting in a double-loop channel furnaces

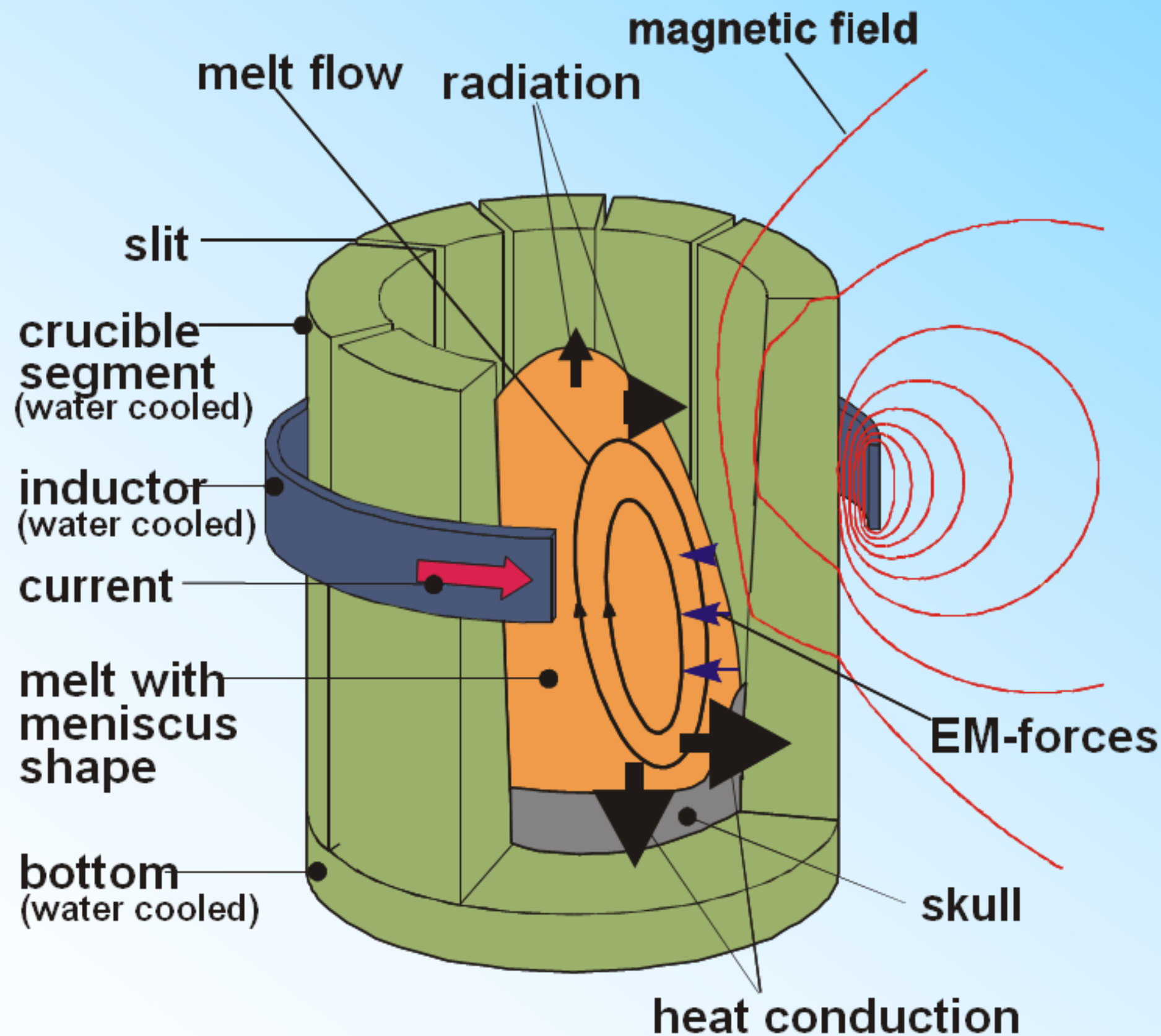
Development of Induction Melting: After 1945

ASEA, Sweden was the leading company in the development of **large channel induction furnace**. The main aim was the increase of power.

For aluminium melting, the trend to built larger furnaces could be observed, too. After solving serious problems with the formation of deposits in the channels, the lifetime of the refractory linings and the melt motion including pinch effects, **Brown, Boveri & Cie. installed really large furnaces.**

The ceramic free **induction melting of reactive materials in water cooled crucibles (Siemens, 1931)** has been meanwhile developed to a industrially used technology for the manufacture of TiAl motor valves, turbine blades and other parts.

Development of Induction Melting: After 1945



Cold crucible induction furnace



Cold crucible induction furnace for the melting of high purity materials, such as TiAl:

- Slitted copper crucible guarantees electromagnetic transparency
- Intensive electromagnetic stirring of the melt
- Water cooling leads to skull formation
- Overheating of the melt depends on heat losses by conduction

Development of Induction Melting: After 1945

Many other innovations have been developed over the years, but it is impossible to refer to all of them.

- **The optimum design and dimensioning of modern induction melting and heating installations requires suitable digital codes for all necessary calculations.**
- **The mathematical models as well as the numerical simulation of all interesting features of that equipments also reflects the present state of the art.**
- **Therefore, a close cooperation between academia and industry is nowadays as necessary as 90 years ago.**

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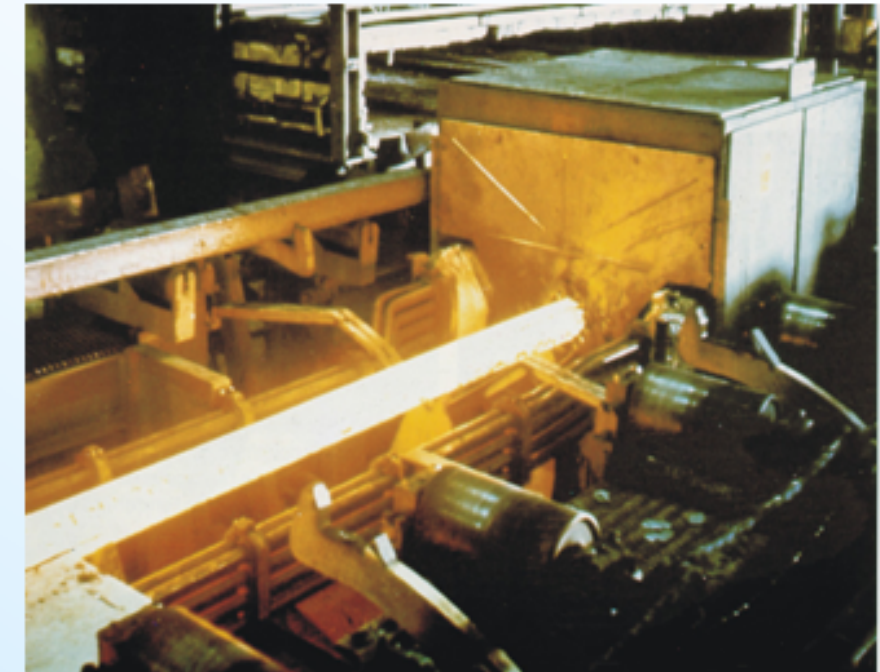
Development of Induction Heating: After 1945

Induction heating of bars, billets or slabs for hot forming has been one of the main applications for many years. Catch words like

- **Rapid heating**
- **Gradient heating**
- **Multi layer bars inductor**

may illustrate some innovative technologies.

Many other innovations have been developed over the years, but it is impossible to refer to all of them.



Development of Induction Heating: After 1945

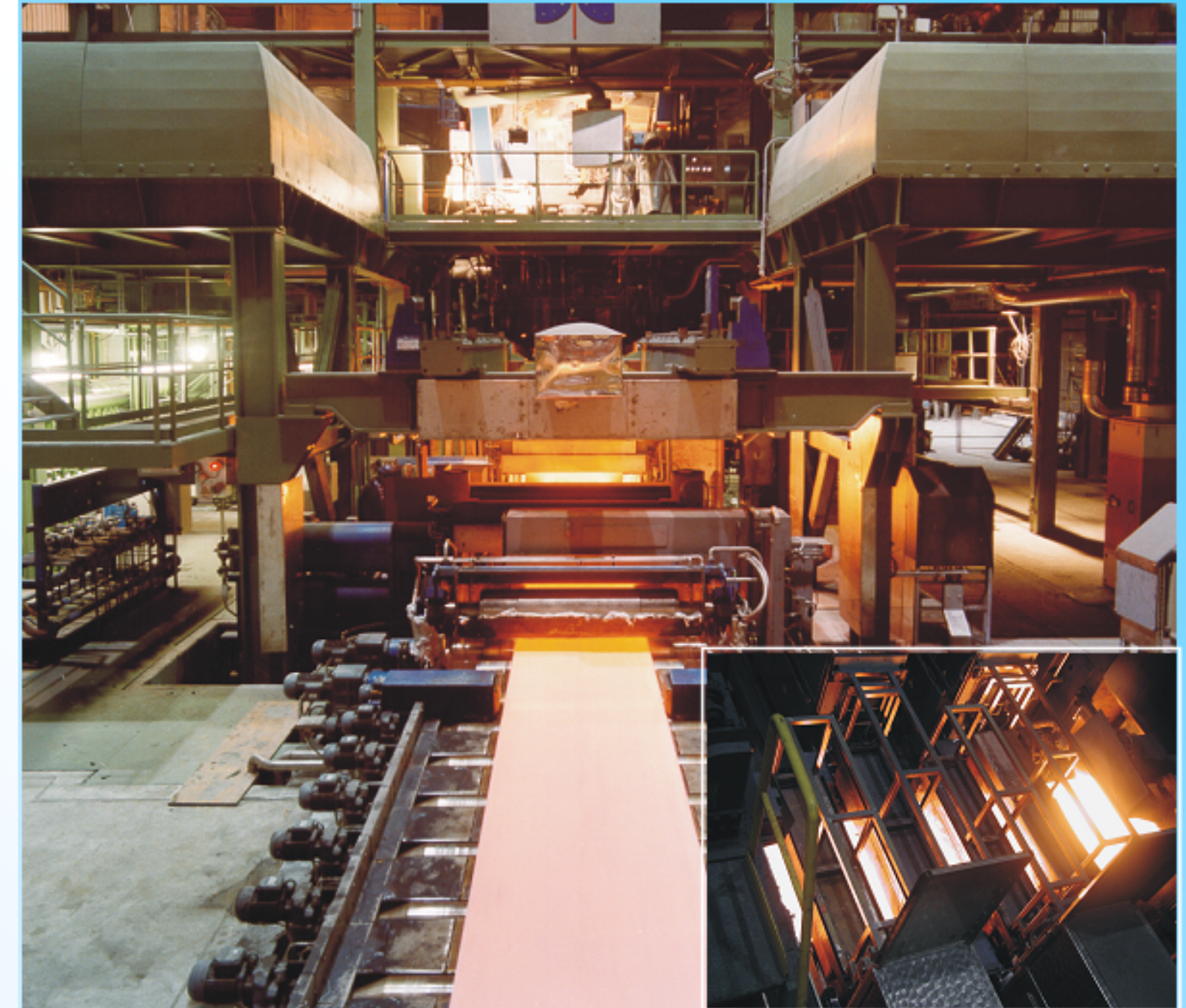
A special innovative technology is the

➤ **Transverse flux induction heating,**

particular for the heating of thin metallic strip in rolling mills and for galvanizing purposes.

This heating method has been already described in the 40s by **V. P. Vologdin** in Russia and years later by **R. M. Baker** in the USA.

It offers nowadays, after further intensive R & D work, many advantages. Heating concepts exist that provide flexibility in width of the strip to be heated and in adjustable temperature profiles over the strip width.



10-MW transverse flux induction heater

Strip Thickness: 1.8 mm to 4.5 mm

Strip width: 1,100 mm to 1,450 mm

Maximum speed of casting: 150 m/min

Casting capacity: 400,000 t/year

In-line heating: > 1,000 °C

Development of Induction Heating: After 1945

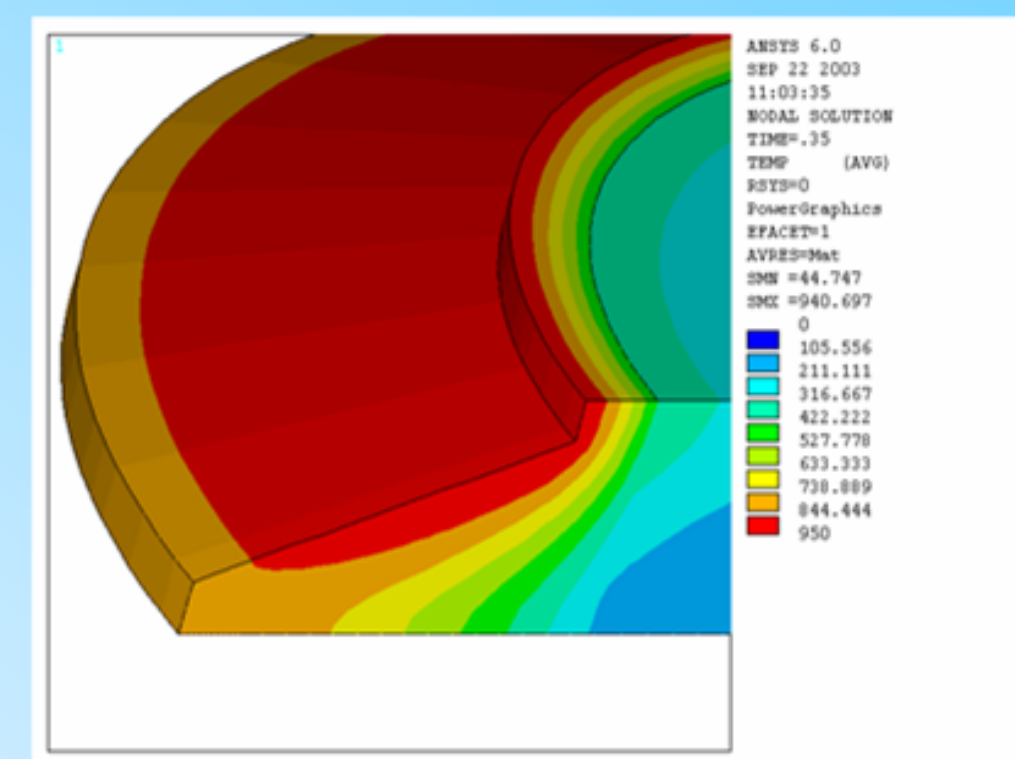
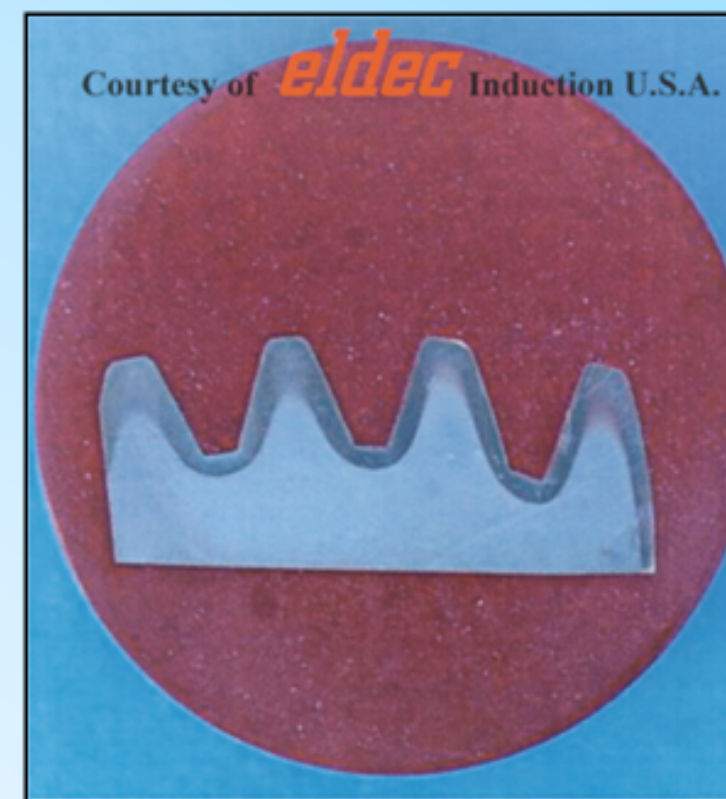
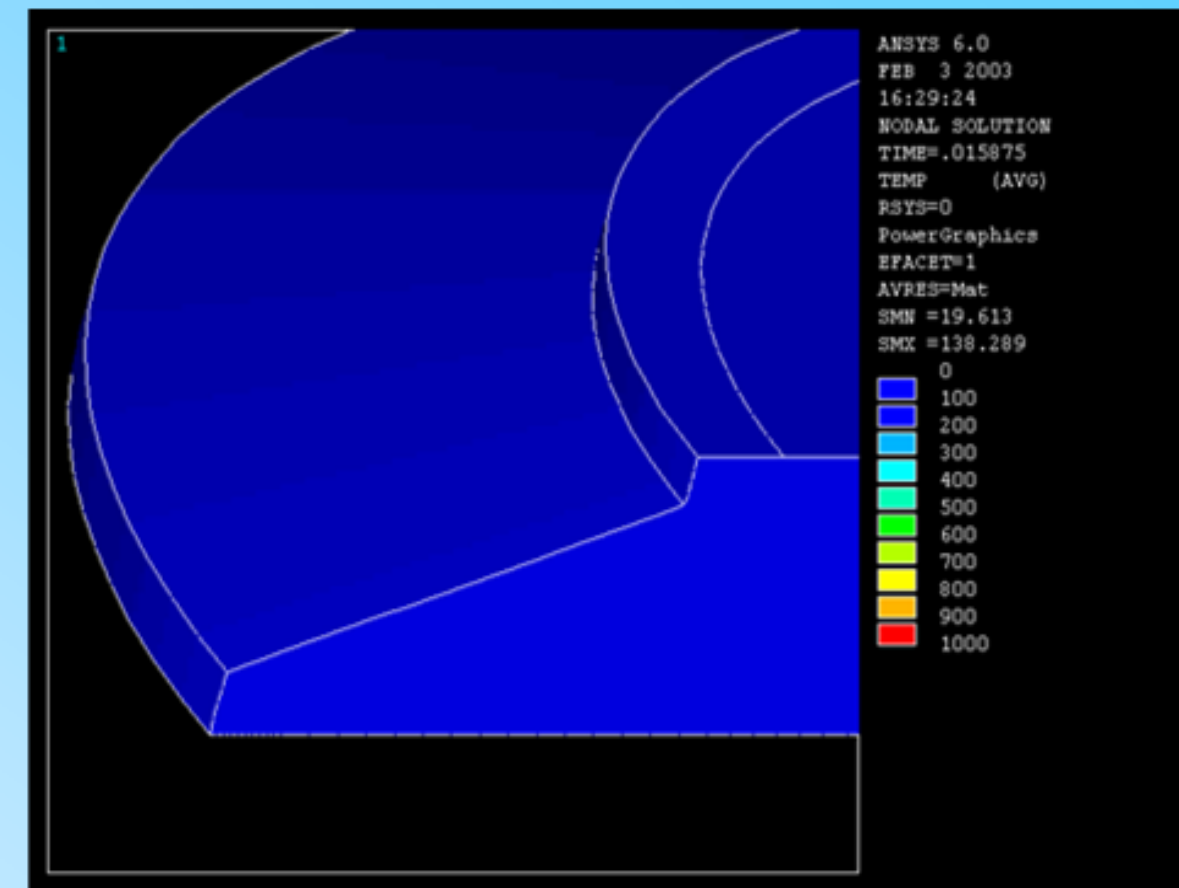
General benefits of

Induction Surface Heat Treatment are

- short heating times
- flexible adaptation to the hardening tasks
- close computerized process control
- compatibility with automation

Here only the **single shot, dual frequency contour hardening** should be treated briefly.

For the highly stressed gears a uniform hardness contour all around the periphery is required. The dual frequency system uses both, MF and HF currents, but they are simultaneously applied in a single-shot to only one coil. By now an optimum selection of the frequencies and the power ratio MF/HF is possible by using modern tools of mathematical modelling and numerical simulation.



Dual frequency heating for optimum hardened contours

Development of Induction Heating: After 1945

Another and last innovative process is the

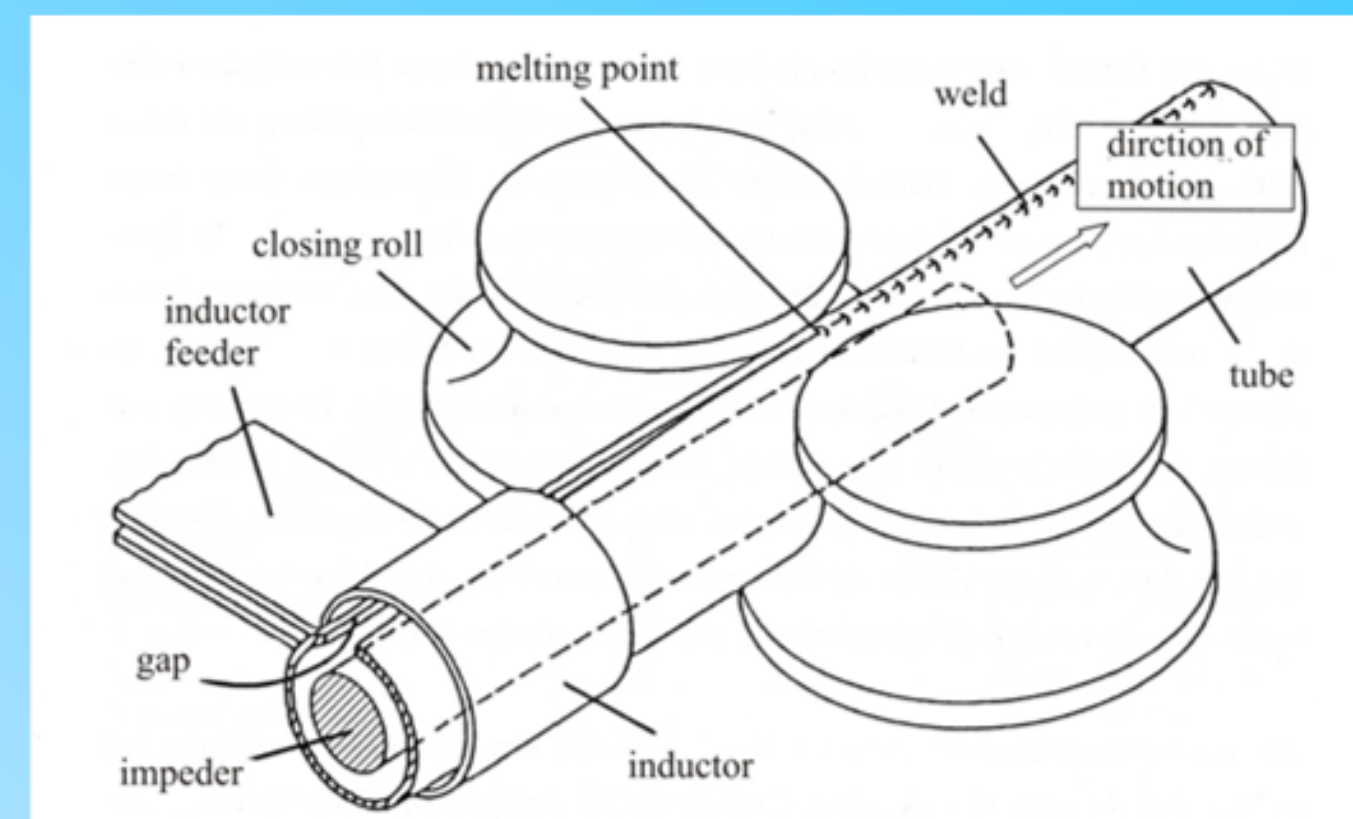
➤ High frequency tube welding.

Strip from a coil is formed to a tubular shape and then fed to closing rolls, where its edges are compressed.

A cylindrical one turn inductor embracing the tube is mounted in front of the final closing rolls.

Current is induced in the tube via the electromagnetic field of the inductor and flows along the tube perimeter beneath the inductor. At the gap, the major part of the current flows along the strip edges and converges at the point of contact.

Welding **speed is from 30 m/min to 120 m/min** depending on the wall thickness; the frequencies used are in the range of several hundred kHz and solid state converters are state of the art.



High frequency induction tube welding

Conclusions

This historical overview shows the development of induction melting and heating over a period of more than 100 years.

Many excellent scientists and engineers from all over the world have contributed to shape this discipline and have created many theoretical and practical results.

This report is a first attempt to treat this very interesting subject from a current point of view, but it is by no means fully complete.

It is an obvious challenge for me and others to describe the history of the various heating methods in more detail and more comprehensive.

This must be one of the future tasks with the final objective, to describe the history of electro thermal processes in total.

