The CERN Accelerator School

RF for Accelerators – a travel through history

Christine.Vollinger@cern.ch

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I wish to give credits for this talk to

Maurizio Vretenar from CERN

who spent quite some time in its preparation and shared his slides with me…

THANK YOU!

The history

From Maxwell to the Radio

1864: Maxwell’s equations.

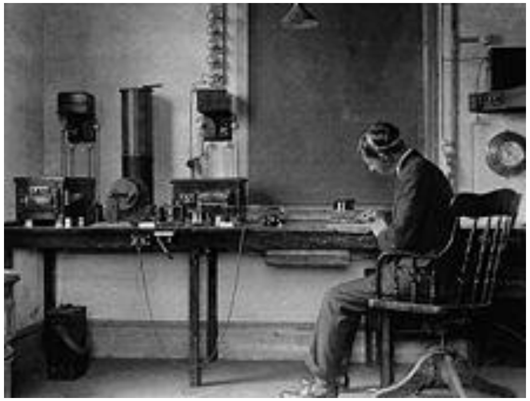
$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

1873, Maxwell: Theoretical basis of wave propagation.

1888, Hertz: Experimental generation/reception of EM-waves.

1891, N. Tesla, G. Marconi and others: wireless telegraph.

1905-14: development of early vacuum tubes
(De Forest, triode in 1907).



1914-18: war effort led to large quantities of tubes produced, cost goes down. Improved technology: operation in vacuum (Langmuir, 1915), filament coating (1920).

1919-20: first attempts to broadcast with vacuum tubes using AM modulation, in the kHz range.

1920-25: start of regular radio broadcasting in most countries
(1920: Argentina, US; 1923: Germany 100 years ago!).

From Rutherford to…
the Particle Accelerator

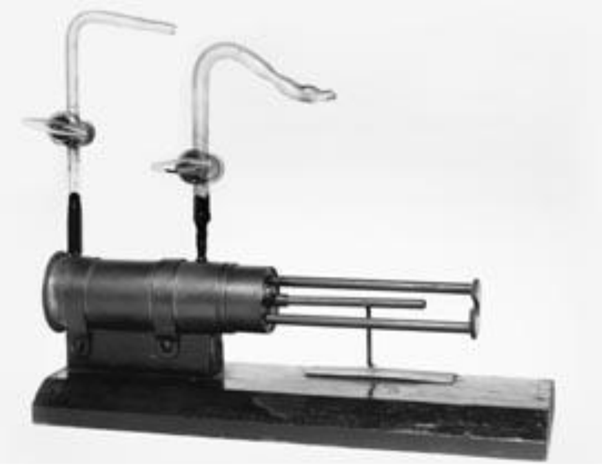
After WWI starts the quest for high-energy particle accelerators capable to disintegrate the nucleus

→ transform the matter, the dream of the ancient alchemists!

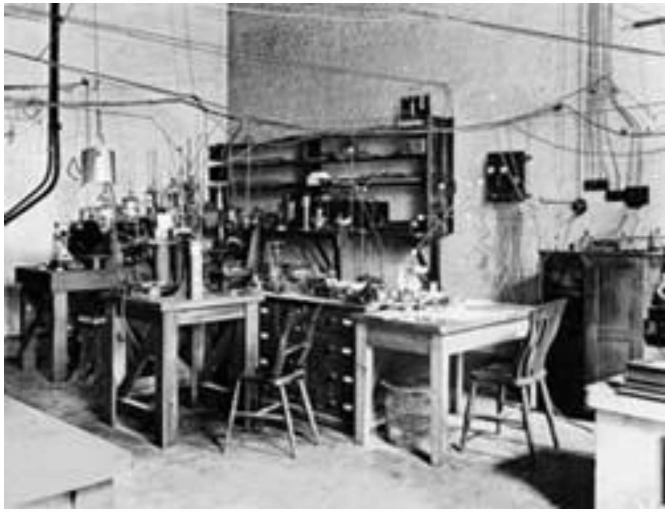
1919: E. Rutherford experiment: a nitrogen nucleus is disintegrated by natural α-particles (Radium and Thorium) → start of a new era for science! However, by using particles from radioactive decays only few light atoms can be modified.

1927: Rutherford in a speech at the Royal Society asks for "accelerators" capable to disintegrate heavy nuclei.

Theory predicts the threshold for penetration of the nucleus at ~500 keV → from 1929, various labs start developing "particle accelerators" for >500 keV.



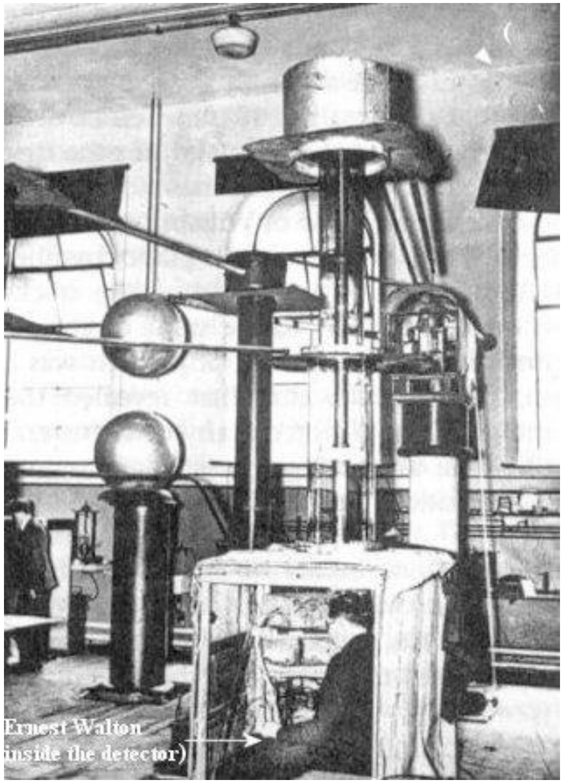
Reproduction of the Rutherford chamber: Bombardment of nitrogen atoms with alpha particles, producing oxygen and hydrogen nuclei.



The Early Accelerators

1927 to 1932, development of electrostatic accelerators:

1. Cockcroft and Walton (Cavendish Lab, Cambridge) → extend to higher voltages the "voltage multiplier" used for X-ray production.
2. Van de Graaf (Princeton) → develop the belt-charged static generator.
3. Others explore pulsed techniques, capacitor discharges, transformers, etc.



And the winners are…. Cockcroft and Walton, who in 1932 obtain disintegration of lithium by 400 keV protons. But:

- higher energies are necessary to disintegrate heavier nuclei in quantities;
- DC technologies are limited by breakdown to few MeV.

→ A new technology is needed…

The first Radio-Frequency accelerator: R. Wideröe’s thesis…

Rolf Wideröe: a Norwegian student of electrical engineering at Karlsruhe and Aachen. The X-ray transformer that he had chosen for his PhD Thesis at Aachen University did not work, and he was forced to choose quickly another subject. Inspired by a 1924 paper from Ising, a Swedish professor (acceleration of particles using “voltage pulses”), in 1928 he put together for his thesis a device to demonstrate the acceleration of particles by RF fields:

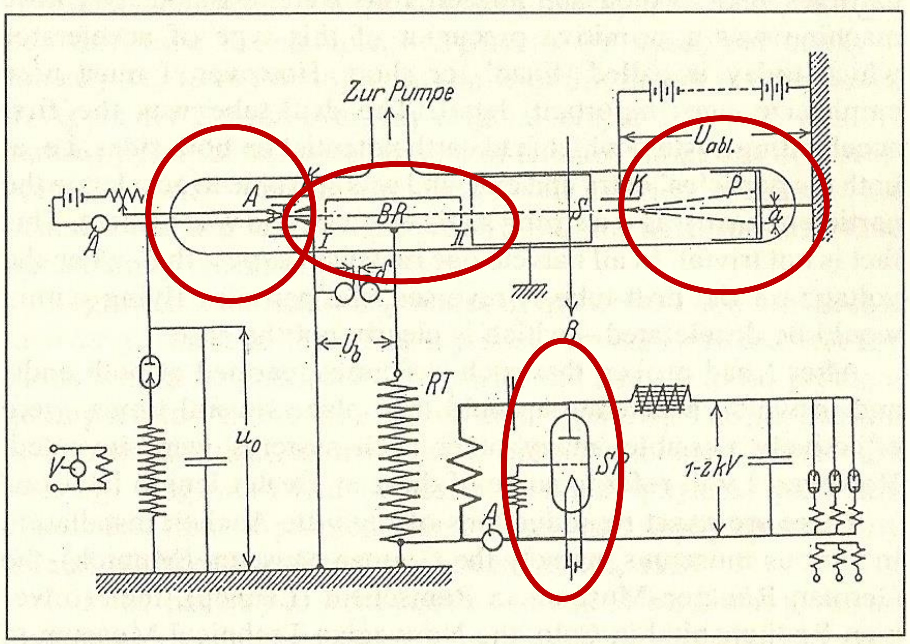


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

Acceleration of potassium ions 1+ with 25kV of RF at 1 MHz → 50 keV acceleration (“at a cost of four to five hundred marks”…)

1. use of a triode and of radio technology (at the time limited to 1-2 MHz) ⟶ marrying radio technology and accelerators.
2. Use of a drift tube separating 2 accelerating gaps → invention of synchronous RF accelerators.
3. complete accelerator: ion source, RF acceleration, detector, all in vacuum

Great start and a new obstacle…

Limitation of the Wideröe device:
for protons, needs high frequencies

($d = \beta\lambda/2$, → taking d~10 cm, W=500 keV → f~50 MHz, λ ~6 m)

☞ But a) higher frequencies were not possible with the tubes of the time;
b) losses from a conventional circuit would have been too large!

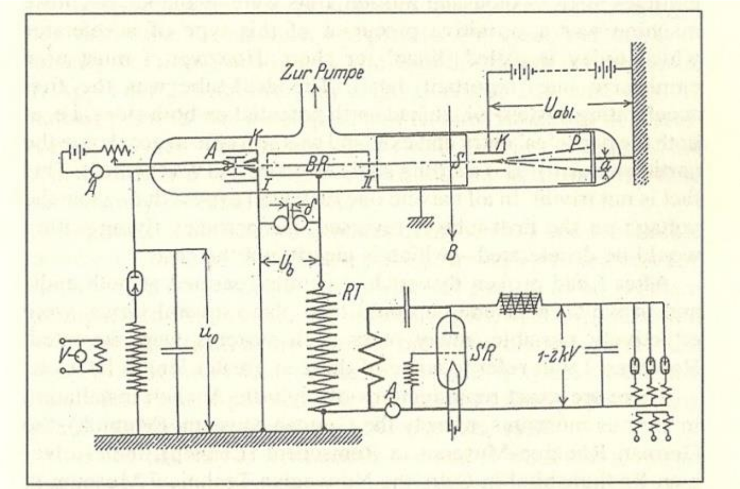


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

→ after the PhD, Rolf Wideröe works for AEG to build HV circuit breakers and his thesis, published in the "Archiv für Elektrotechnik", remains unnoticed.

… But the topic was hot!

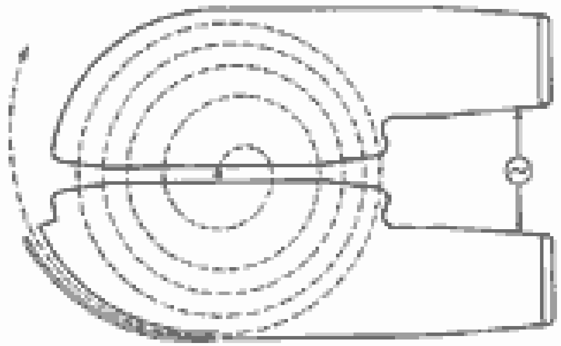
From Aachen to… Berkley
An idea travels the world.

In the 1920's, Ernest O. Lawrence (born 1901), young professor of physics at Berkeley, wants to join the "energy race", and is looking for a new idea…

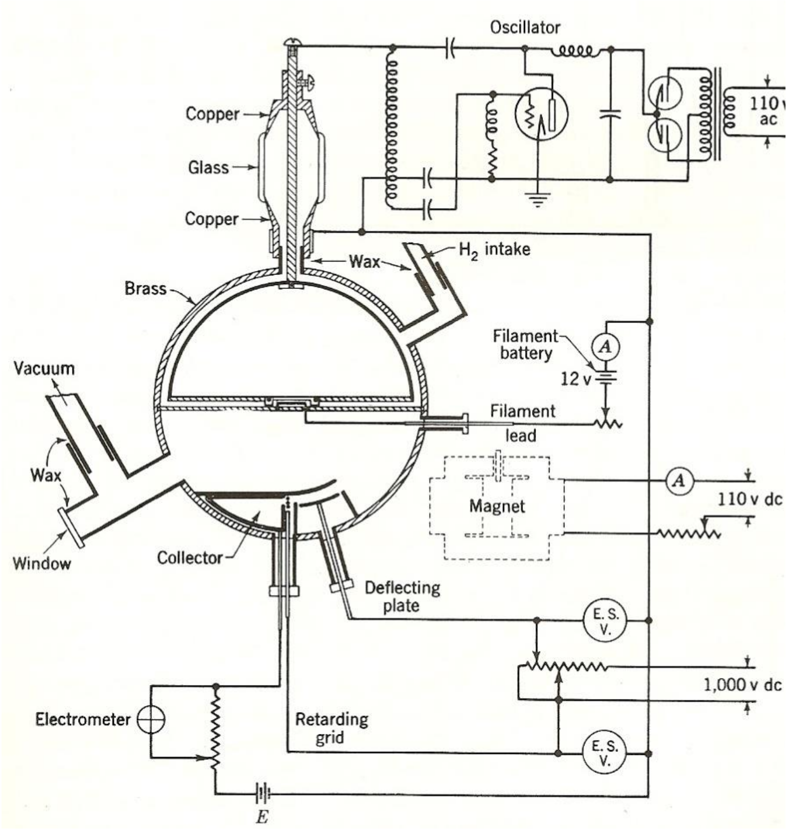
In 1929, during a conference, he goes to the university library and finds Wideröe's thesis in the 1928 "Archiv für Elektrotechnik" (but he did not speak German…).

Immediately, he realised the potential of Radio-Frequency acceleration, and starts to work with his PhD students on 2 parallel activities:

1. A Wideröe "linac" with several drift tubes, to accelerate heavy ions (Sloan and Lawrence).
2. A "cyclic" accelerator, bending the particles on a circular path around Wideröe's drift tube (Livingston and Lawren
→ the cyclotron.



The cyclotron – the first RF accelerator



1. Acceleration in the gap between two "D" → long path of the particles in the D, frequencies ~1 MHz can be effectively used (3.5 MHz, 1st Berkeley cyclotron).
2. Fortunate "coincidence": the revolution frequency does not depend on the beam energy → RF frequency is constant !

   (but: this limits the use of cyclotron to non-relativistic energies !)

1931: the Berkeley cyclotron reaches **1.2 MeV**.
First atom disintegrations in 1932.

1934: **5 MeV** reached on a new larger machine (used for the production of neutrons, discovered just in 1932).

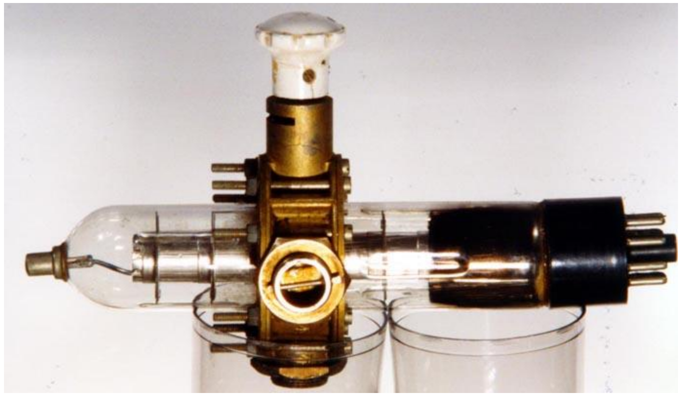
Higher frequencies – klystrons and cavities

Early RF systems were limited by leakage of RF power at high frequencies

→ William Hansen (b. 1909) at Berkeley starts to work on “cavity resonators” for higher frequency.

→ In 1937 Hansen moves to Stanford University where in 1937-39 together with the Varian brothers develops a new source of RF power, the klystron (pseudo-greek from κλυσ- action of waves breaking against a shore).

In 1948 the Varians left Stanford to start their company (Varian Associates) and produce commercial klystrons → the klystron goes from accelerators to industry, and will equip the new TV broadcasting stations.


A WW2 3 Ghz klystron

Note that:

the original klystrons worked at mW levels, only after the war MW-level klystrons were developed at Stanford.

From industry to accelerators: WW II and the radar

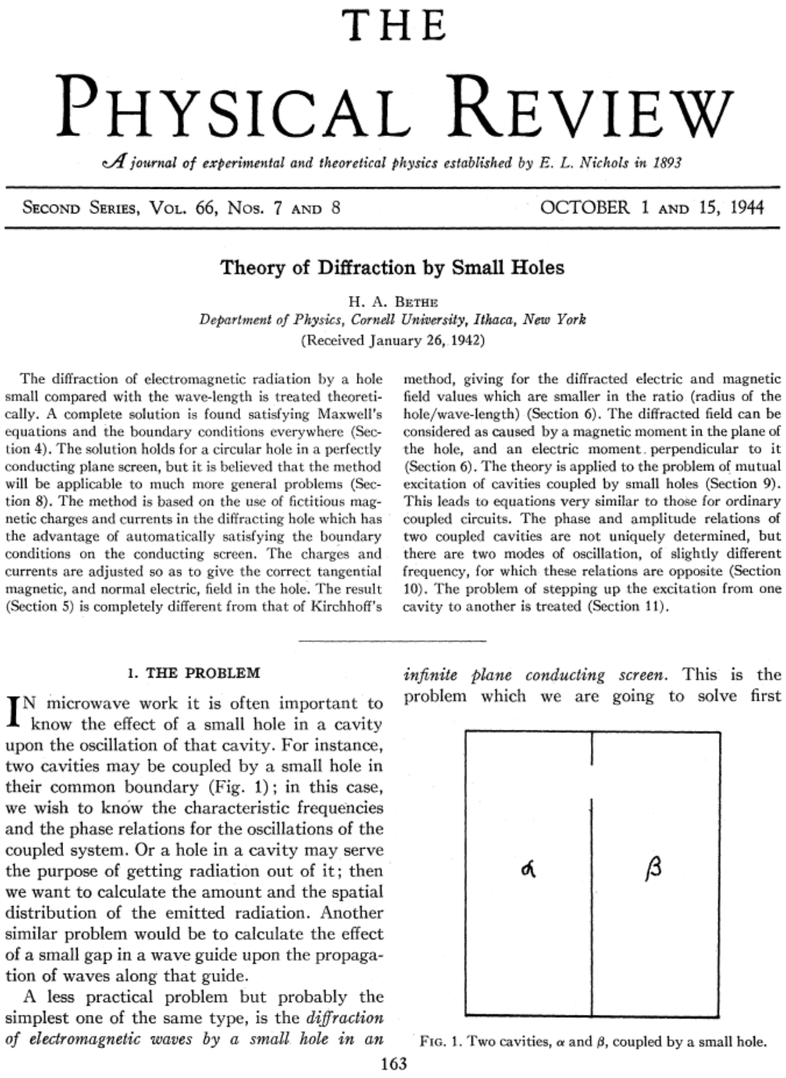
The war effort recruited the best UK and US scientists: the klystron team at Stanford and the cyclotron team at Berkeley contribute to the development of radars.

In 1940, the Radiation Laboratory at MIT established, which will develop the modern radar technology.

Note that early radars were based on the magnetron (= electron tube where electron flow is controlled by magnetic fields), developed at Birmingham in 1930-40 (3-30 GHz).

UK radar technology was shared with US from 1940.

Scientists at the RF war… an example



THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 66, NOS. 7 AND 8 OCTOBER 1 AND 15, 1944

Theory of Diffraction by Small Holes

H. A. BETHE
Department of Physics, Cornell University, Ithaca, New York
(Received January 26, 1942)

The diffraction of electromagnetic radiation by a hole small compared with the wave-length is treated theoretically. A complete solution is found satisfying Maxwell's equations and the boundary conditions everywhere (Section 4). The solution holds for a circular hole in a perfectly conducting plane screen, but it is believed that the method will be applicable to much more general problems (Section 8). The method is based on the use of fictitious magnetic charges and currents in the diffracting hole which has the advantage of automatically satisfying the boundary conditions on the conducting screen. The charges and currents are adjusted so as to give the correct tangential magnetic, and normal electric, field in the hole. The result (Section 5) is completely different from that of Kirchhoff's method, giving for the diffracted electric and magnetic field values which are smaller in the ratio (radius of the hole/wave-length) (Section 6). The diffracted field can be considered as caused by a magnetic moment in the plane of the hole, and an electric moment perpendicular to it (Section 6). The theory is applied to the problem of mutual excitation of cavities coupled by small holes (Section 9). This leads to equations very similar to those for ordinary coupled circuits. The phase and amplitude relations of two coupled cavities are not uniquely determined, but there are two modes of oscillation, of slightly different frequency, for which these relations are opposite (Section 10). The problem of stepping up the excitation from one cavity to another is treated (Section 11).

1. THE PROBLEM

IN microwave work it is often important to know the effect of a small hole in a cavity upon the oscillation of that cavity. For instance, two cavities may be coupled by a small hole in their common boundary (Fig. 1); in this case, we wish to know the characteristic frequencies and the phase relations for the oscillations of the coupled system. Or a hole in a cavity may serve the purpose of getting radiation out of it; then we want to calculate the amount and the spatial distribution of the emitted radiation. Another similar problem would be to calculate the effect of a small gap in a wave guide upon the propagation of waves along that guide.

A less practical problem but probably the simplest one of the same type, is the *diffraction of electromagnetic waves by a small hole in an infinite plane conducting screen*. This is the problem which we are going to solve first

FIG. 1. Two cavities, α and β, coupled by a small hole.

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Hans Bethe and the coupling cavity-waveguide

Theoretical physicist (nuclear physics, interaction particles/matter, …)

Escaped to UK and then USA in 1933.

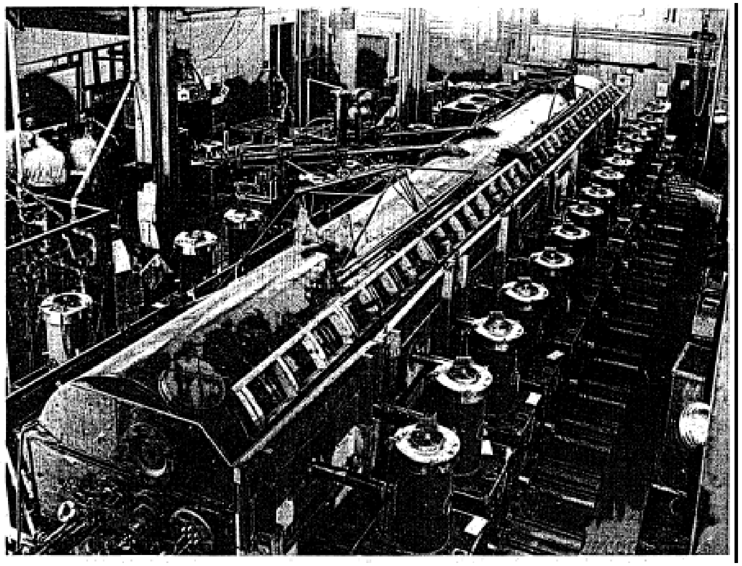
In 1941/42 was asked to contribute to the MIT work on radar, and given the problem of calculating the coupling from a hole between 2 cavity resonators.

The result was this paper, still the basis for understanding coupling problems in RF.

From 1942, Bethe left the RF field for the Manhattan Project, becoming one of the fathers of the atomic bomb.

After the war, the big jump

Luis Alvarez and the Drift Tube Linac



The war effort gave the competences and the components to go to higher frequencies (in the MHz – GHz range) and to try acceleration of a proton beam to the MeV range using the Wideröe principle.

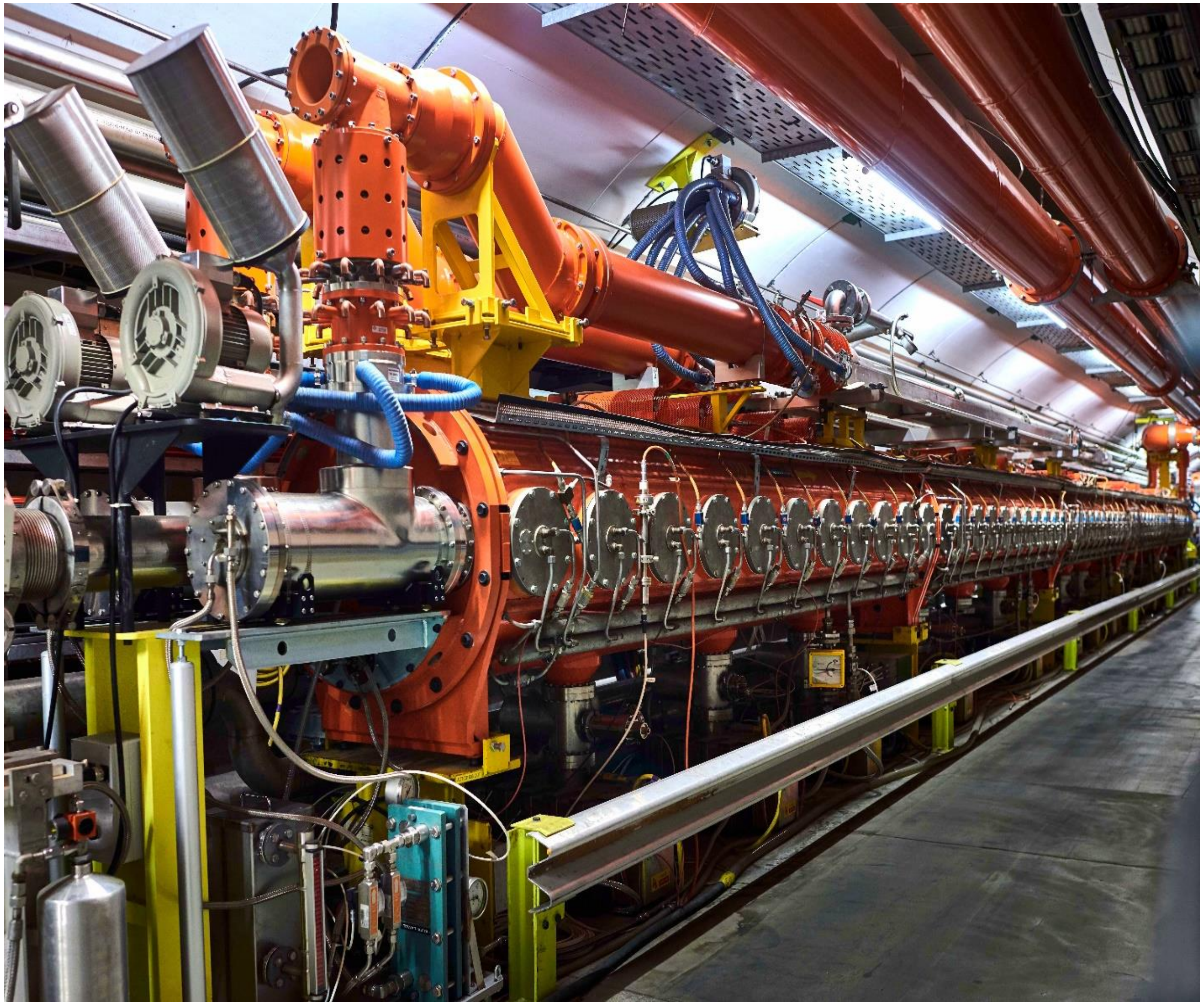
The 1st Drift Tube Linac by L. Alvarez and his team at Berkeley, reaches 32 MeV in 1947.

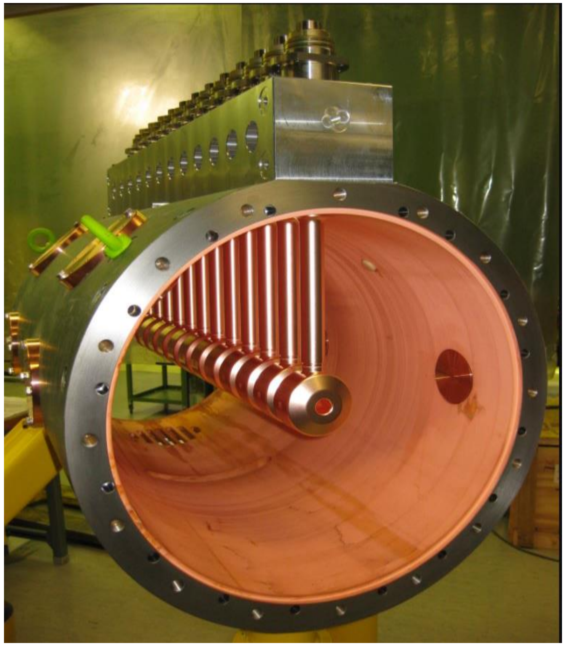
Alvarez, a physicists, worked at MIT on radar during the war. In 1945, he had the tools and the competences to build his own accelerator.

1. The "drift tubes" are inside a cavity resonator.
2. **Frequency** : Alvarez receives from the US Army a stock of 2'000 (!) surplus **202.56 MHz** transmitters, built for a radar surveillance system. 26 were installed to power the DTL with a total of 2.2 MW. They were soon replaced because unreliable, but this frequency remained as the standard linac frequency.

The “linac standard” – still used today!

SPS 200 MHz travelling wave cavity (16m long).





Alvarez drift tube structure, CERN

Another jump: higher frequencies and higher power

William Hansen (right) and colleagues with a section of the first electron linear accelerator that operated at Stanford University in 1947. It was 3.6 meters long and could accelerate electrons to 6 MeV.

The Stanford Linear Accelerator

Development of the first electron linac (Ginzton, Hansen, Kennedy, 1948) at Stanford University.

Travelling-wave structures, iris loaded.

3 GHz chosen as the highest frequency for which power sources were available (magnetron, 1 MW).

The Stanford team develops in 1946-49 a high-power klystron (8 MW) for its new linac.

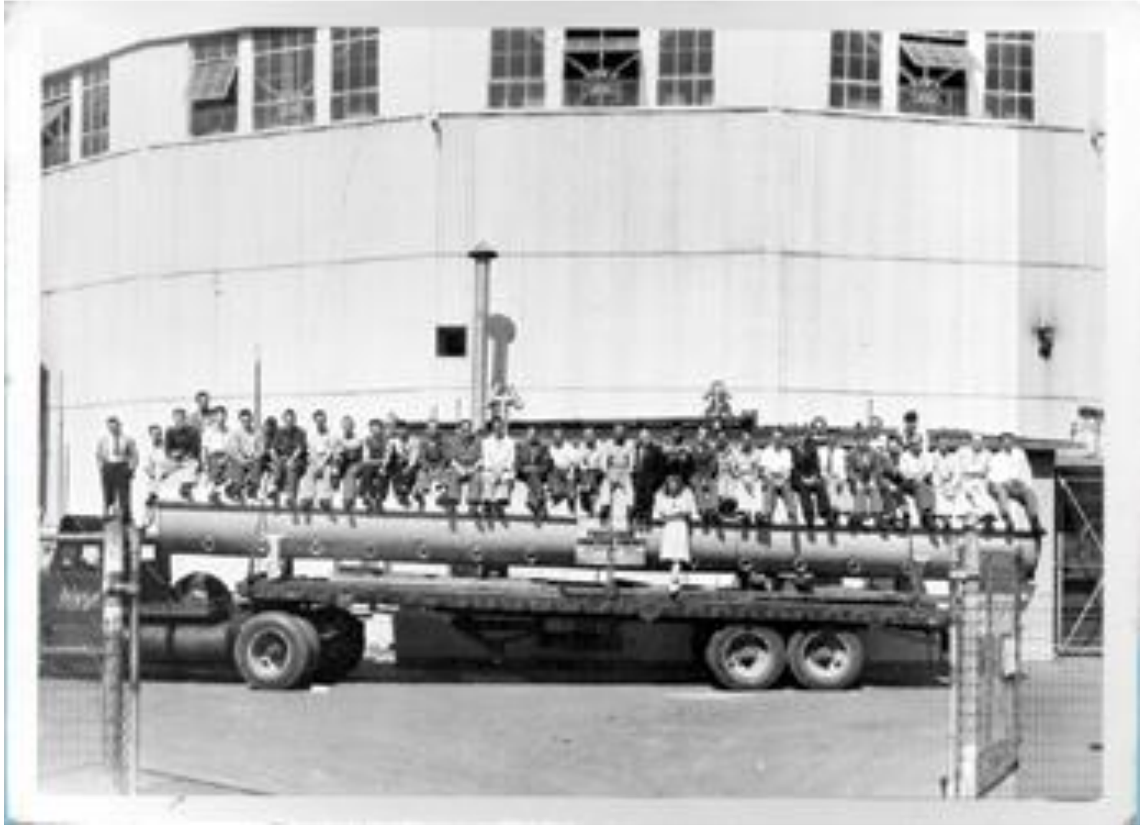
The klystron design was then passed to Varian, which commercialized a whole lot of radar, broadcasting and defence klystrons.

In 1961 Ginzton becomes Chairman of Varian Inc.

Interaction science – industry !

A visual comparison between high and low frequencies…

The previous photograph was advertising the advantages of the 3 GHz frequency… compared to a famous photo of Alvarez’s 1st tank at 202 MHz!



Berkeley Laboratory group seated on top of the vacuum tank of their 40-foot 32-MeV proton linear accelerator on the back of a flatbed truck, probably in 1947.

After linacs came new RF challenges: the proton synchrotron

Goal was: going to the relativistic range → Construction of early Proton Synchrotrons from 1952.

New RF problems: relatively small voltages (~kV/turn) but variable frequency during acceleration to keep synchronism (from ~100 kHz to ~5 MHz).

Resonators heavily loaded with ferrites in air → ferrite technology + ceramic gap technology (for insulation from the machine vacuum).

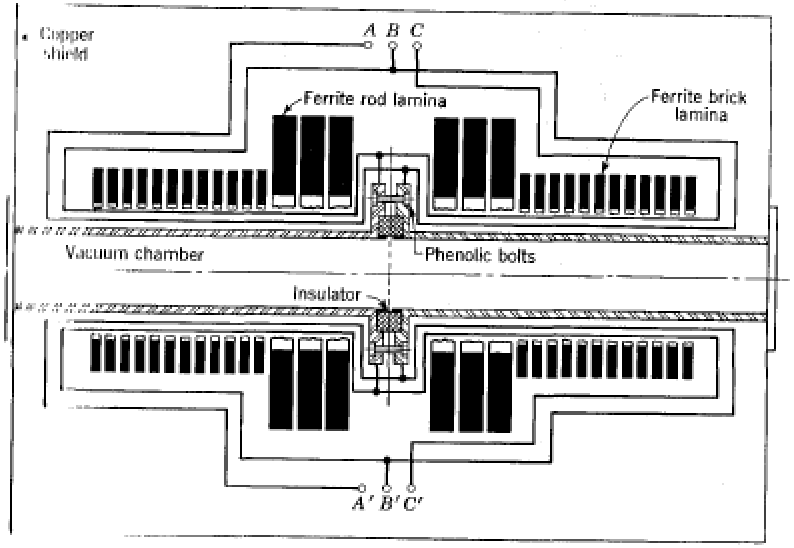


Fig. 13-14. Ferrite-core accelerating unit for the cosmotron.

Scheme of the RF cavity of the Brookhaven Cosmotron (1952, 3 GeV beam energy)

Ferrite-loaded cavities

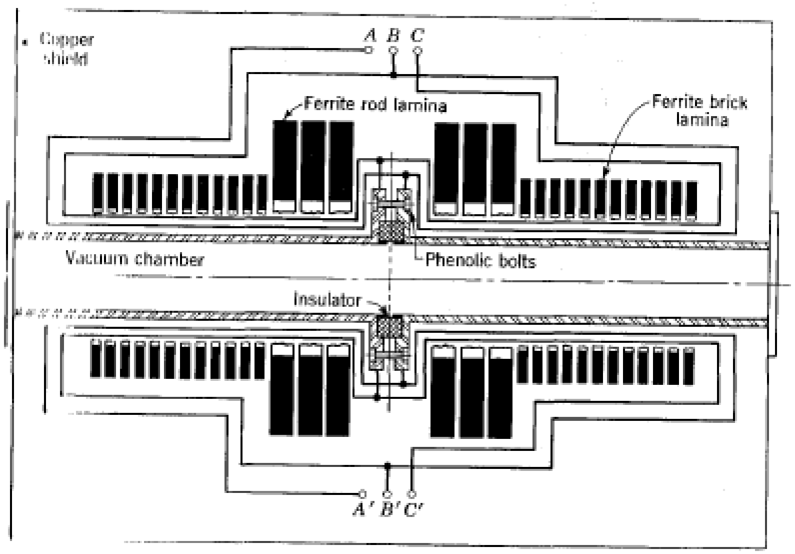
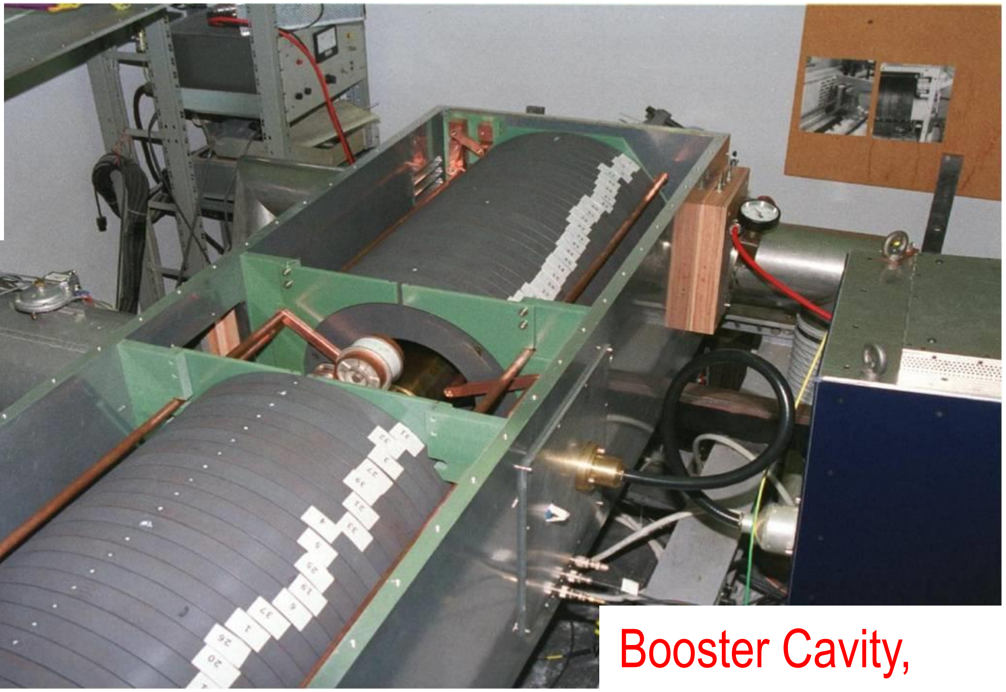


Fig. 13-14. Ferrite-core accelerating unit for the cosmotron.

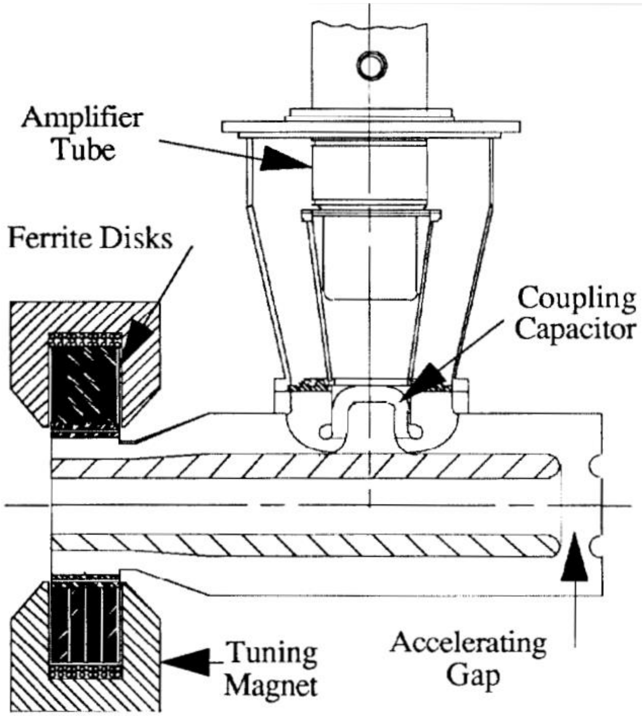
Same principle like the original cosmotron idea (= ferrite biasing with figure-of-8-current loops) was running in the PSB of CERN for many years.



Booster Cavity, below 20 MHz

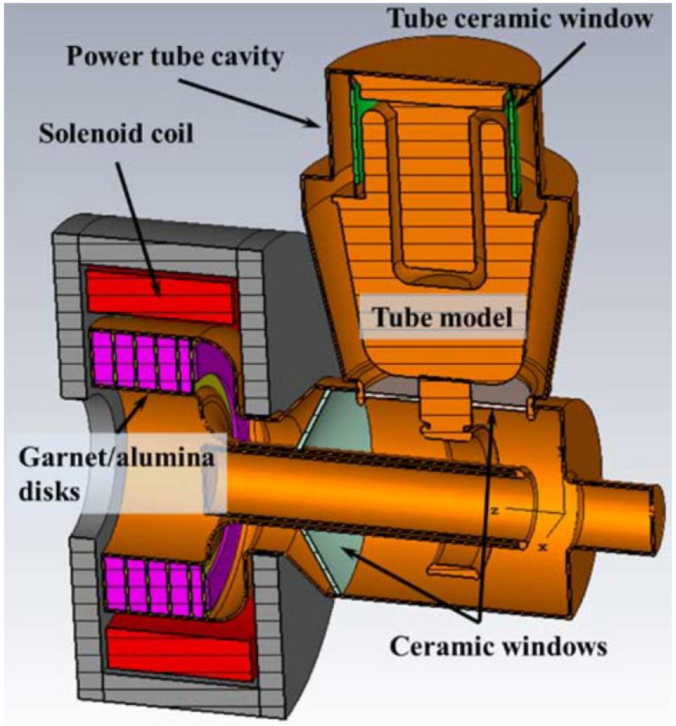
Tunable cavities at higher frequencies

SSC Low Energy Booster,
~47 MHz to 60 MHz



C. C. Friedrichs et al., PAC91, p. 1020

FNAL Booster 2nd harmonic,
76 MHz – 106 MHz, 100 kV



R. L. Madrak, IPAC16, p. 130

… and further development of this idea is still taking place
(different ferrites)

All’s well that ends well…

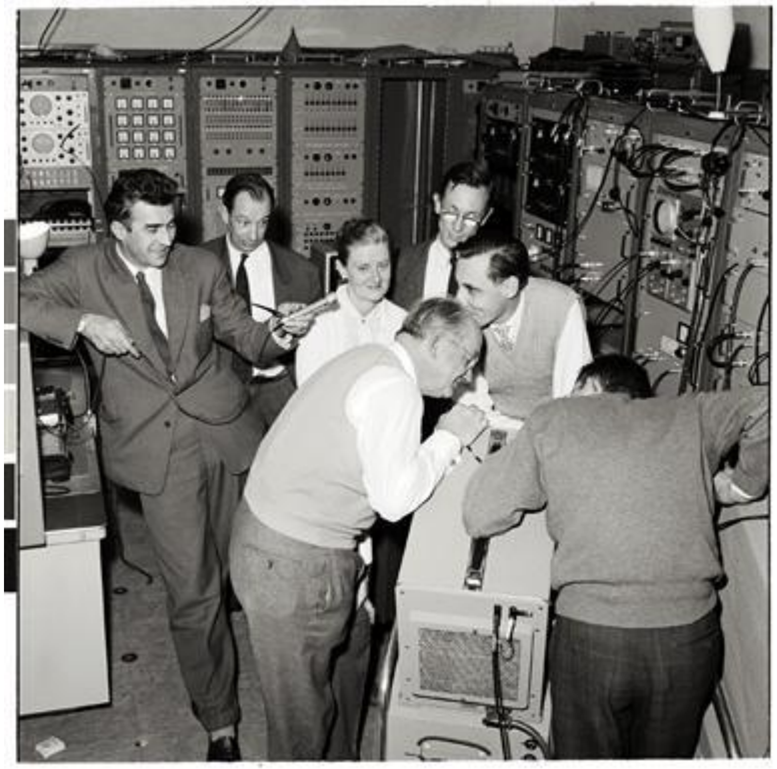
RF is at the forefront of accelerators

The RF team (around Wolfgang Schnell) brought the smile to the team that was commissioning the CERN PS, the first alternating gradient synchrotron in the world.

The machine for months <u>could not cross</u> transition. All worked well, but beam was regularly lost at transition.

Schnell had a personal theory on why the beam was lost, and hastily put together in a Nescafe tin a circuit to switch the phase of the RF at transition.

The beam went immediately to full energy and Schnell (and RF!) became the hero of the day (24.11.1959).



24.11.1959, during the first hours of the start-up of the PS: J. Adams, H. Geibel, H. Blewett, C. Schmelzer, L. Smith, W. Schnell, P. Germain.

RF Maturity: frequency, power, etc.

And then, it is no longer history…

Since the 60's, we have seen a multiplication of accelerators around the world, each with its own specific RF system, going from the large colliders for physics to the small machines for industrial applications and medicine (> 7'000 electron accelerators for X-ray therapy are operational around the world !).

The trends for the RF systems have been:

- Increase in complexity, in particular for the number and quality of control loops (Low Level RF).
- Increase in frequency, going up to the 30 GHz of the original CLIC proposal;
- Increase in RF power, pulsed or CW: some modern proposals call for GW's of installed RF power.

But in the last 50 years, one particular major breakthrough… Became a game changer

The rise of superconductivity

Superconductivity known since 1911, theoretical understanding (BCS theory) only in 1957.

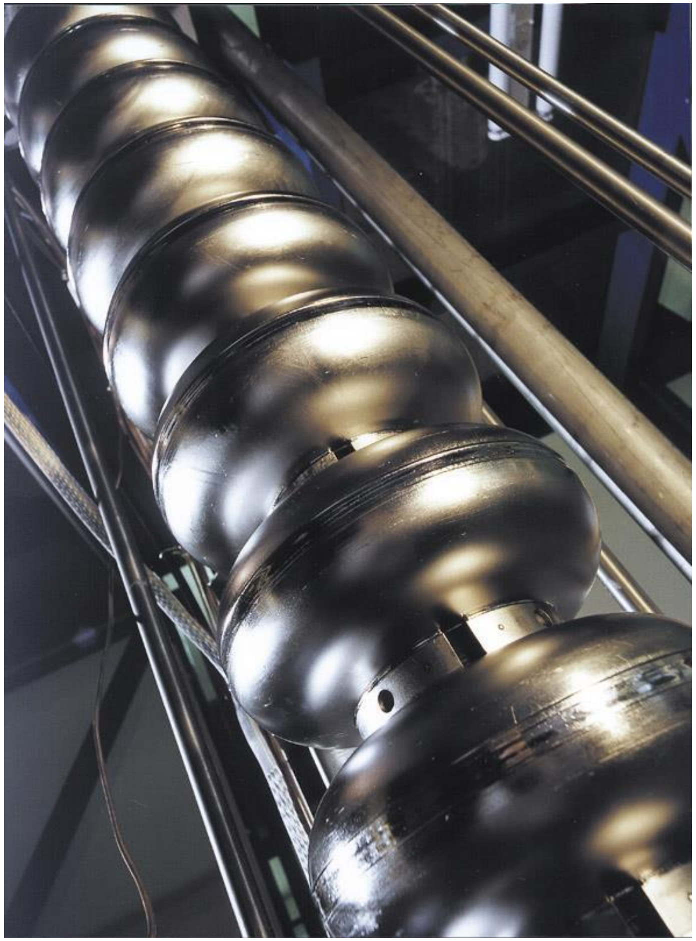
1965: acceleration of electrons at Stanford in a lead-plated SC resonator.

1970's: several SC cavity projects aiming at 2-3 MV/m (Stanford, Illinois, CERN, Karlsruhe, Cornell, Argonne).

Late 70's – 80's: impressive advance in the number of projects and in the gradient achievable, thanks to improved cleaning techniques (plus geometry optimisation and improvement in Nb quality). Gradients > 10 MV/m routinely obtained.

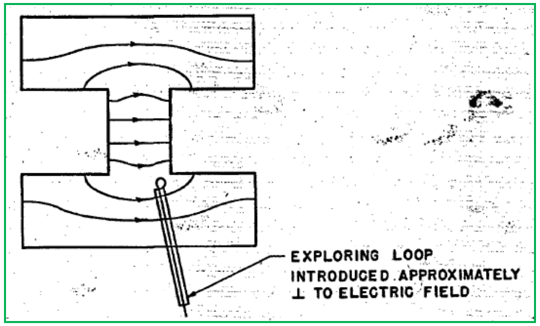
80's - 90's: Large scale SC projects, ATLAS and CEBAF in USA, HERA and LEP-II in Europe.

90's – 00's: impressive development for TESLA and then for the ILC.



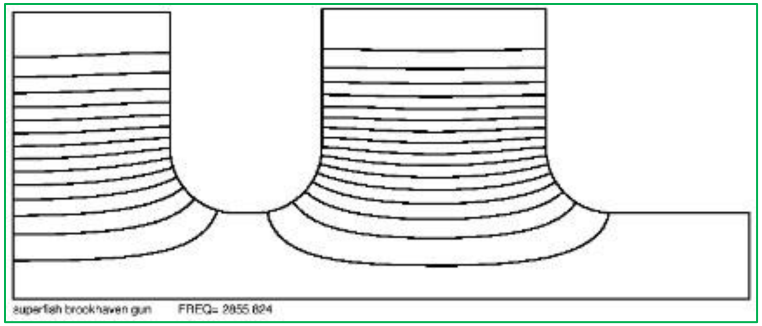
Progress in mapping the EM-fields

Knowledge of the field distribution inside an accelerating cavity is essential to define the operating frequency, to compute the voltage, to dimension the coupler, etc.



1. The good old way: build a model and then measure frequency and explore fields with a probe.

(illustration from the original Alvarez paper on DTL)



2. From the beginning of the 80's, modern computers allow to calculate frequency and fields in 2D (axis-symmetric cavities): SUPERFISH and URMEL.

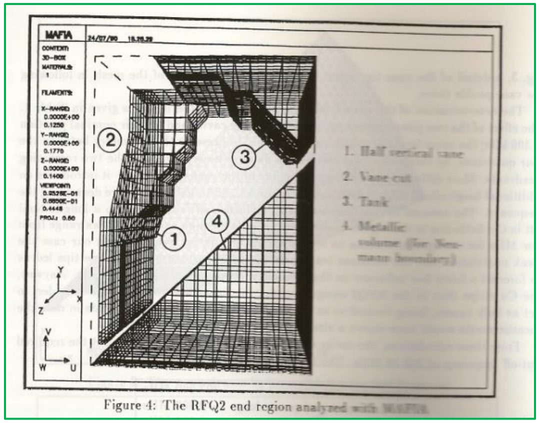


Figure 4: The RFQ2 end region analyzed with MAFIA

3. At the end of the 80's comes the first 3D software: the MAFIA package (DESY and LANL). Constantly improved, 3D packages allow nowadays to calculate complex shapes with amazing precision.

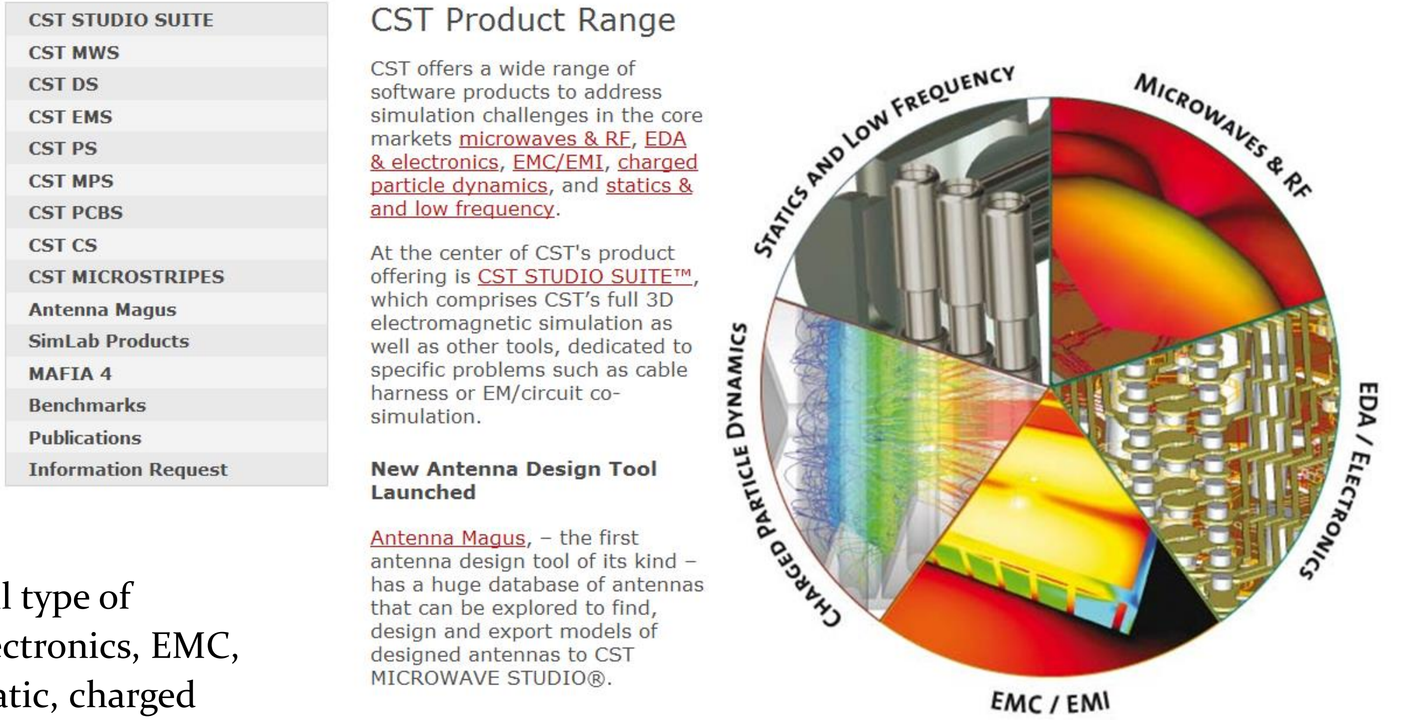
(1^{st} 3D simulation of the CERN RFQ2 – 1987, 6000 mesh points)

3D from science to industry…

3D simulation software was developed at the end of the 80’s for the needs of RF cavities for accelerators.

It has now evolved towards complete packages that are commonly used by microwave and electronics industry.

Example: the product page from the web site of CST, the company commercializing the successors to the MAFIA package.



- CST STUDIO SUITE
- CST MWS
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- CST EMS
- CST PS
- CST MPS
- CST PCBS
- CST CS
- CST MICROSTRIPES
- Antenna Magus
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CST Product Range

CST offers a wide range of software products to address simulation challenges in the core markets microwaves & RF, EDA & electronics, EMC/EMI, charged particle dynamics, and statics & and low frequency.

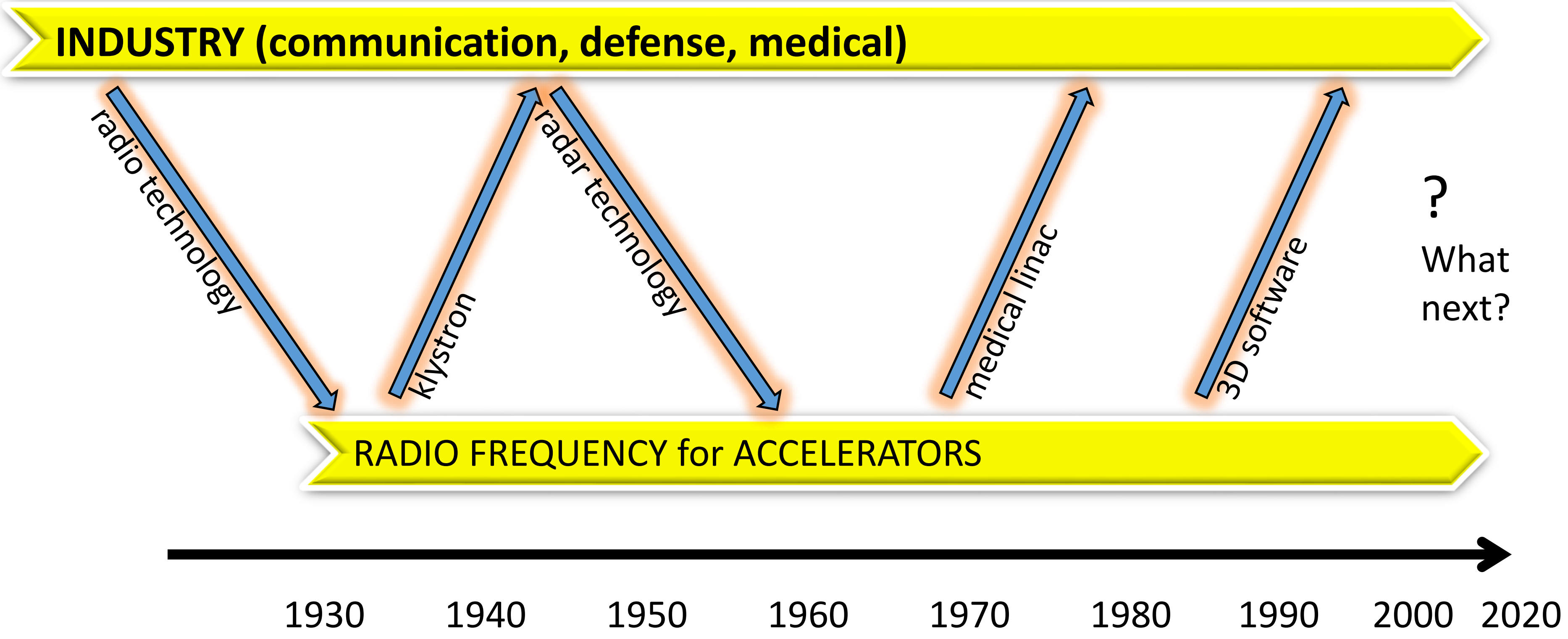
At the center of CST's product offering is CST STUDIO SUITE™, which comprises CST’s full 3D electromagnetic simulation as well as other tools, dedicated to specific problems such as cable harness or EM/circuit co-simulation.

New Antenna Design Tool Launched

Antenna Magus, – the first antenna design tool of its kind – has a huge database of antennas that can be explored to find, design and export models of designed antennas to CST MICROWAVE STUDIO®.

Applications include all type of microwave systems, electronics, EMC, electro and magnetostatic, charged particle dynamics.

Industry and accelerator RF



Plus many more subjects…
Exchange with industry has been very profitable in the early years but more reduced in recent times, mainly because of the absence of collaboration frames.
There is now an effort (by EU and individual governments) to strengthen these links between these 2 parallel lines again → if done correctly, this can be only beneficial to both worlds!

Thank you for your attention!