

RF for Accelerators - an introduction

*A travel through history and anatomy of a technology...
and to the importance of the H factor!*

Maurizio Vretenar - CERN BE/RF
Ebeltoft 2010

1991
1993
2000
2010

1st RF CAS: Oxford (UK)
2nd RF CAS: Capri (I)
3rd RF CAS: Seeheim (D)
4th RF CAS: Ebeltoft (DK)

1. The history

1864: Maxwell's equations.

1873, Maxwell: Theoretical basis of wave propagation.

1888, Hertz: Experimental generation/reception of e.m. waves.

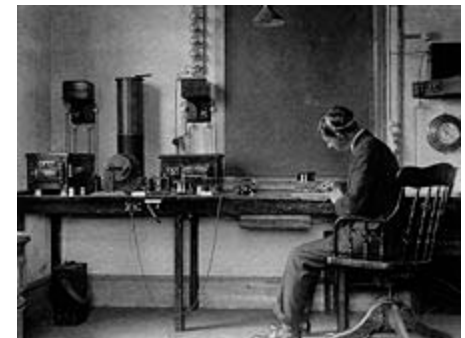
1891, N. Tesla, G. Marconi and others: wireless telegraph.

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

1914-18: large quantities of tubes produced because of war effort, 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).



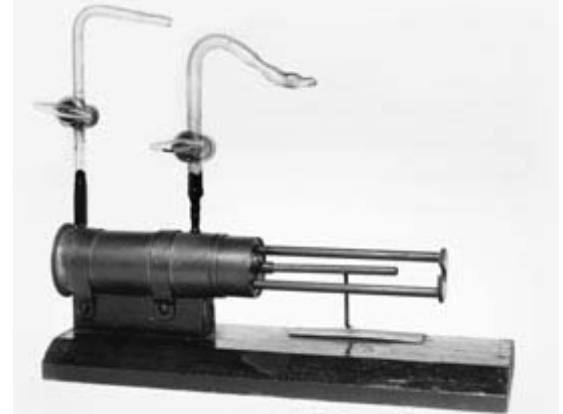
From Rutherford to the Particle Accelerator



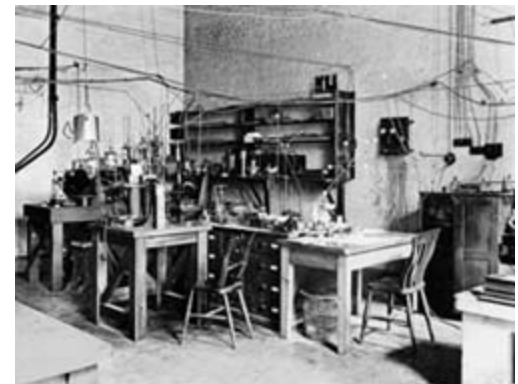
After WWI starts the quest for high-energy particle accelerators capable to disintegrate the nucleus → transform the matter, the dream of the ancient alchemists!

1919: E. Rutherford experiment: a nitrogen nucleus is disintegrated by natural α -particles (from Ra and Th) → start of a new era for science! 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.

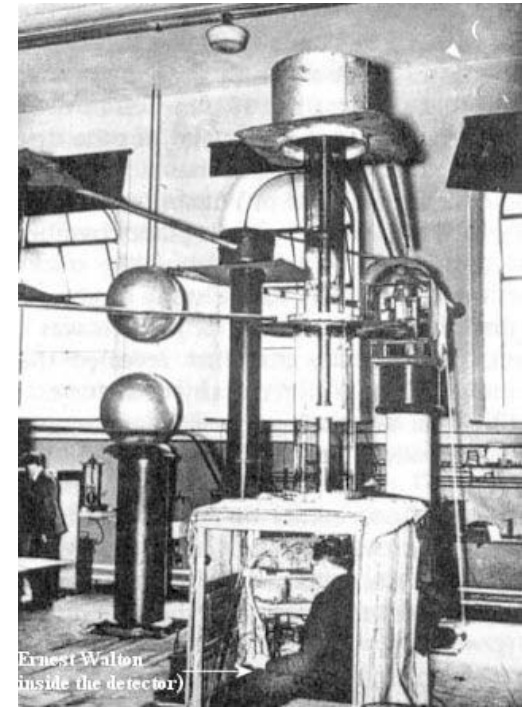


Reproduction of the Rutherford chamber: Bombardment of nitrogen atoms with alpha particles, producing oxygen and hydrogen nuclei.



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...



Who was the first to have the idea of using modern radio technology for particle accelerators?

Remember: the radio was around since 1920, and from 1927 the scientific community was looking for ideas to build high-energy particle accelerators.



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:

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

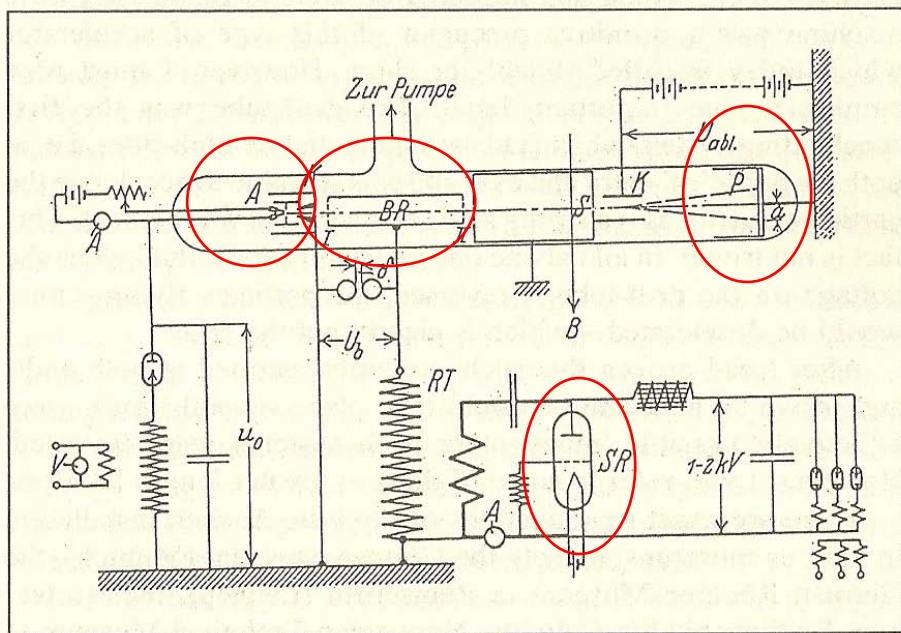


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

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

Limitation of the Wideröe device:

for protons, needs high frequencies

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

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

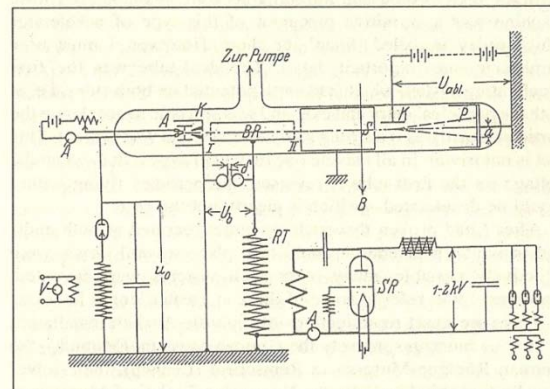


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

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

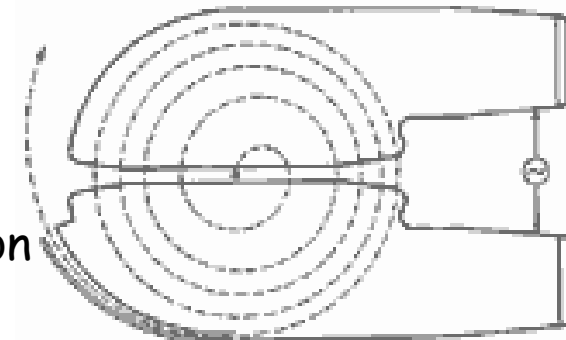
... But the topic was hot!

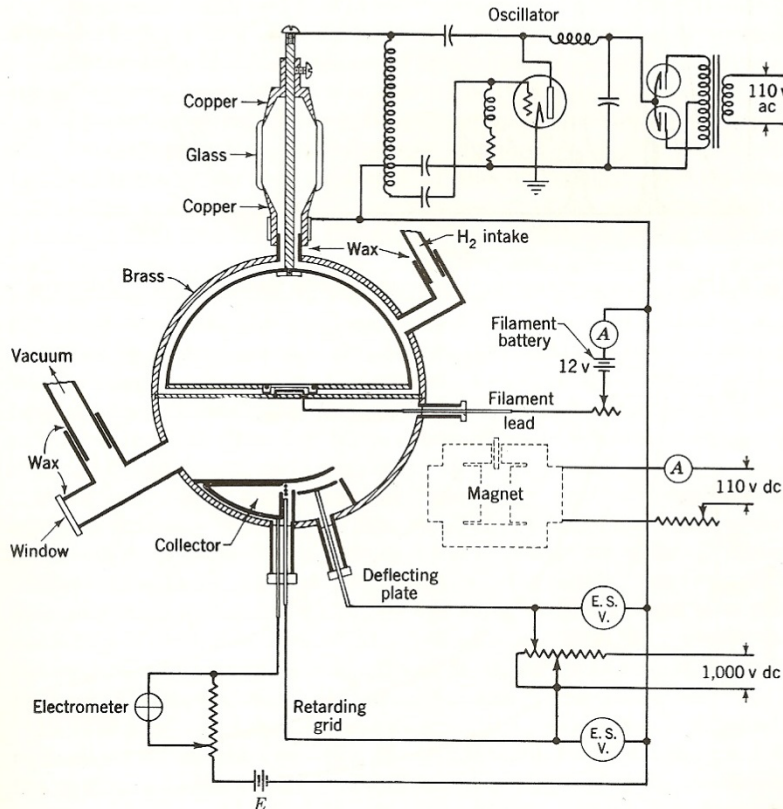
In the 1920's, Ernest O. Lawrence (born 1901), young professor of physics at Berkeley, wants to join the "energy race", and is looking for a new idea...

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 the idea of **Radio-Frequency acceleration**, and starts 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 Lawrence) → the **cyclotron**.





Scheme of the first Berkeley cyclotron, from S. Livingston's PhD Thesis.

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 limit the use of cyclotron to non-relativistic energies !)

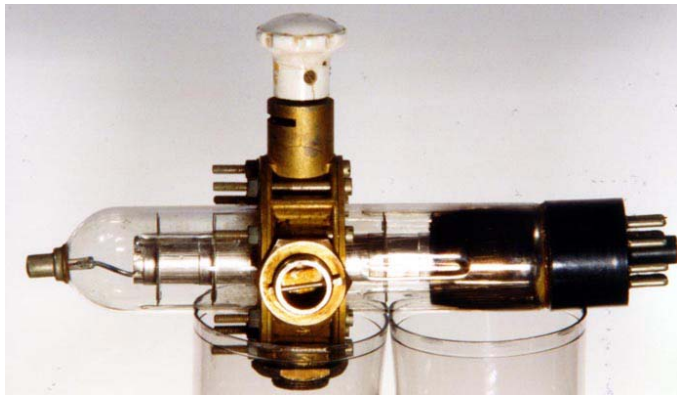
1931: the Berkeley cyclotron reaches 1.2 MeV.
First atom disintegrations in 1932.

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

Early RF systems (LC-based) were limited by leakage of RF power at high freq.

- W. 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

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

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

Note that early radars were based on the magnetron, developed at Birmingham in 1930-40 (3-30 GHz). UK radar technology was shared with US from 1940.

The great boost to RF technology that made modern particle accelerator possible came from the radar development of WW II. All the research at MIT was made public after the war (and produced great series of books on RF technologies).



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

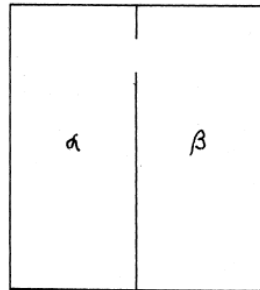


FIG. 1. Two cavities, α and β , coupled by a small hole.

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 atom bomb.



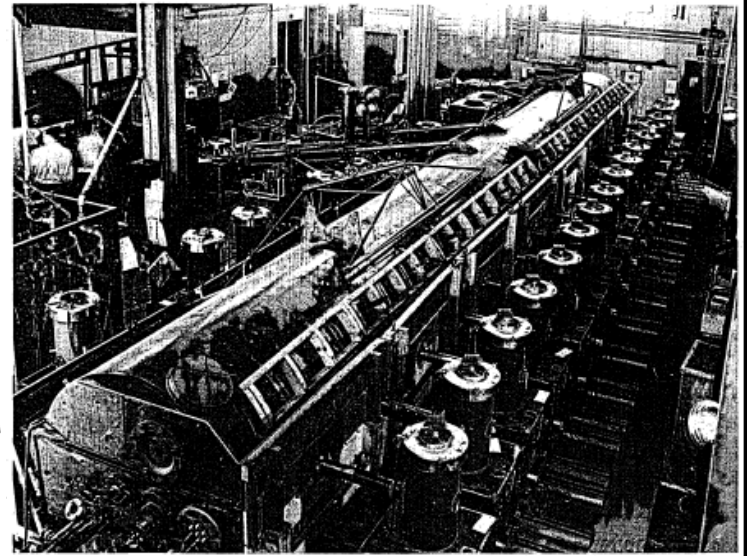
Luis Alvarez and the Drift Tube Linac

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 physicist, worked at MIT on radar during the war. In 1945 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.





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.

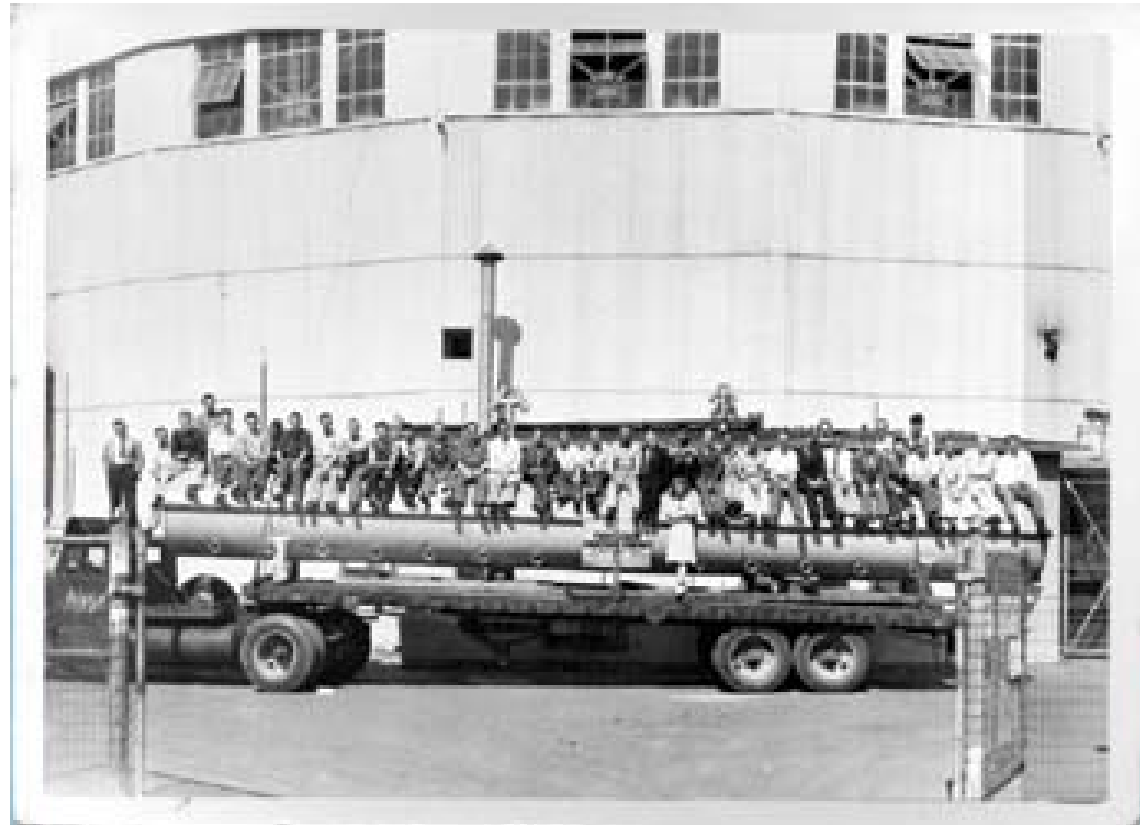
In 1961 Ginzton becomes Chairman of Varian Inc.

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.

Going to the relativistic range → Construction of early **Proton Synchrotrons** from 1952.

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

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

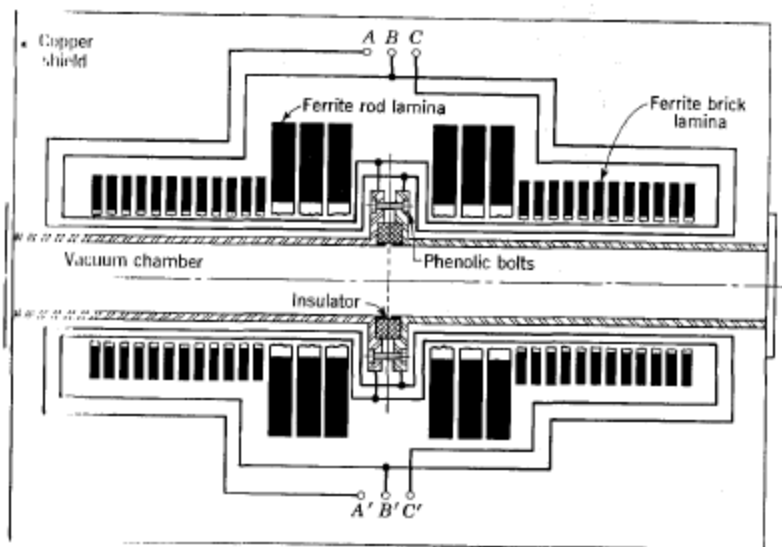


Fig. 13-14. Ferrite-core accelerating unit for the cosmotron.

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

RF at the forefront of accelerators

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

The machine for months could not cross transition. All worked well, but beam was 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.

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, only one major breakthrough...



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

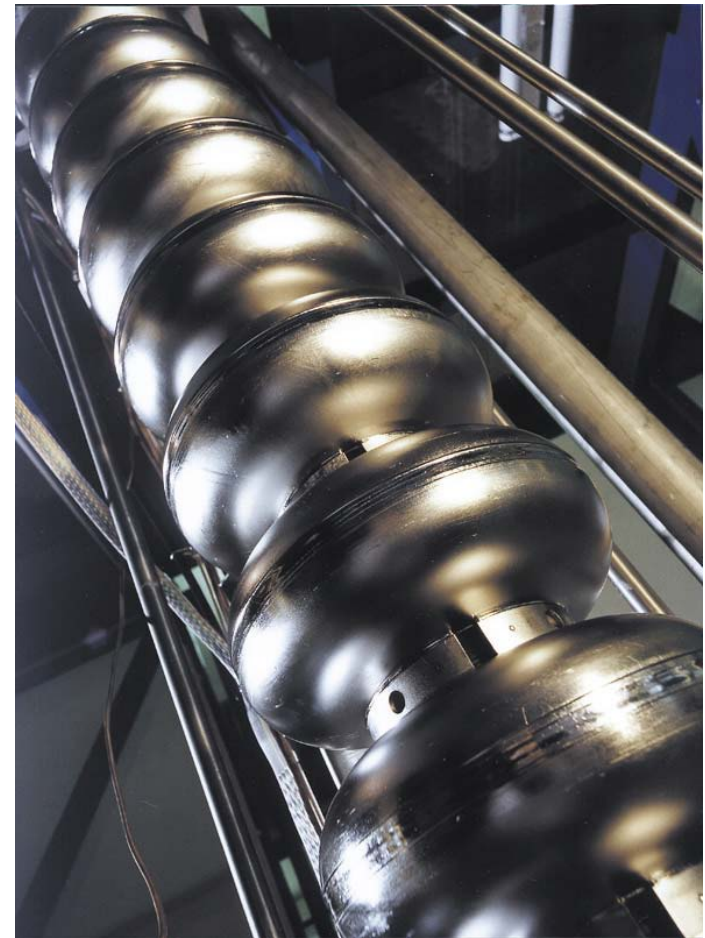
1965: acceleration of electrons at Stanford in a lead-plated SC resonator.

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

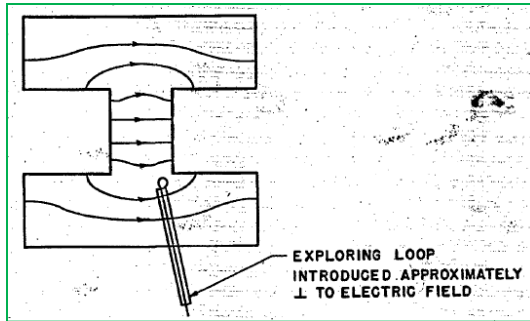
Late 70's - 80's: impressive advance in the number of projects and in the gradient achievable, thanks to improved cleaning techniques (plus geometry optimisation and improvement in Nb quality). Gradients > 10 MV/m routinely obtained.

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.

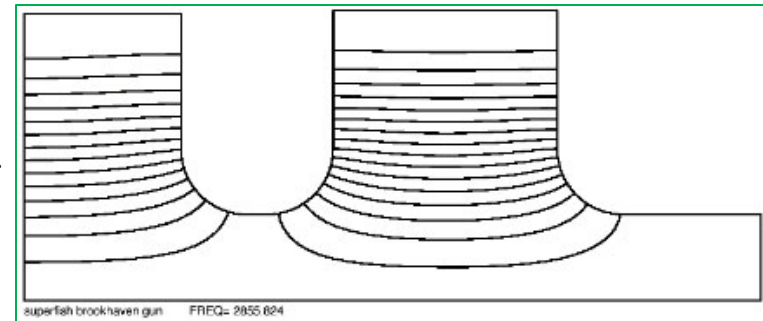


Knowledge of the field distribution inside an accelerating cavity is essential to define the operating frequency, to compute the voltage, to dimension the coupler, etc.



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.

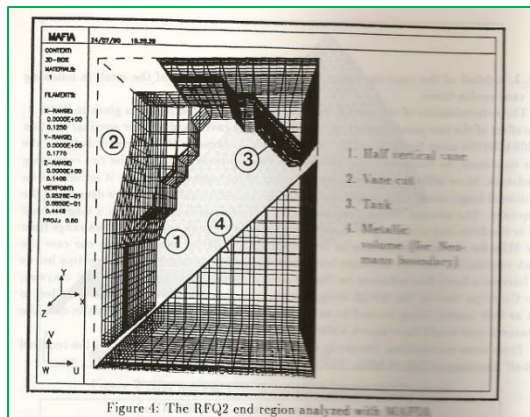


Figure 4: The RFQ2 end region analyzed with MAFIA

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.

(1st 3D simulation of the CERN RFQ2 - 1987, 6000 mesh points)

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
CST DS
CST EMS
CST PS
CST MPS
CST PCBS
CST CS
CST MICROSTRIPES
Antenna Magus
SimLab Products
MAFIA 4
Benchmarks
Publications
Information Request

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

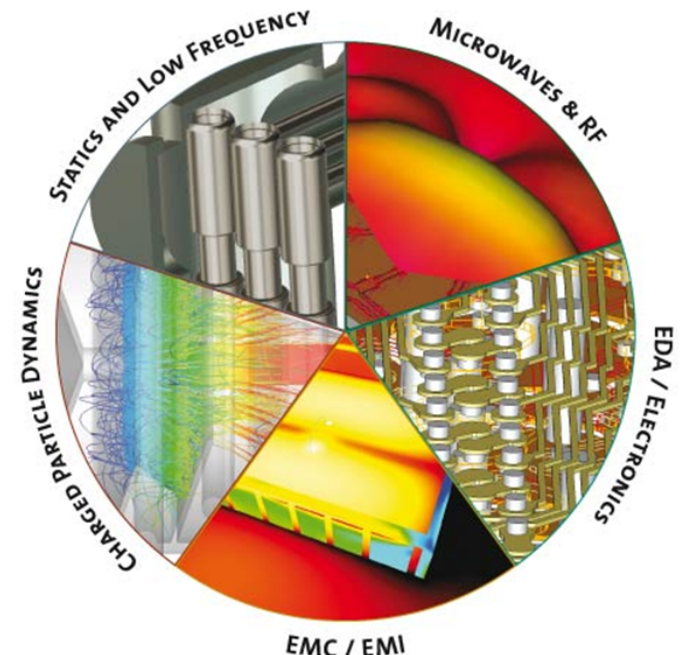
CST Product Range

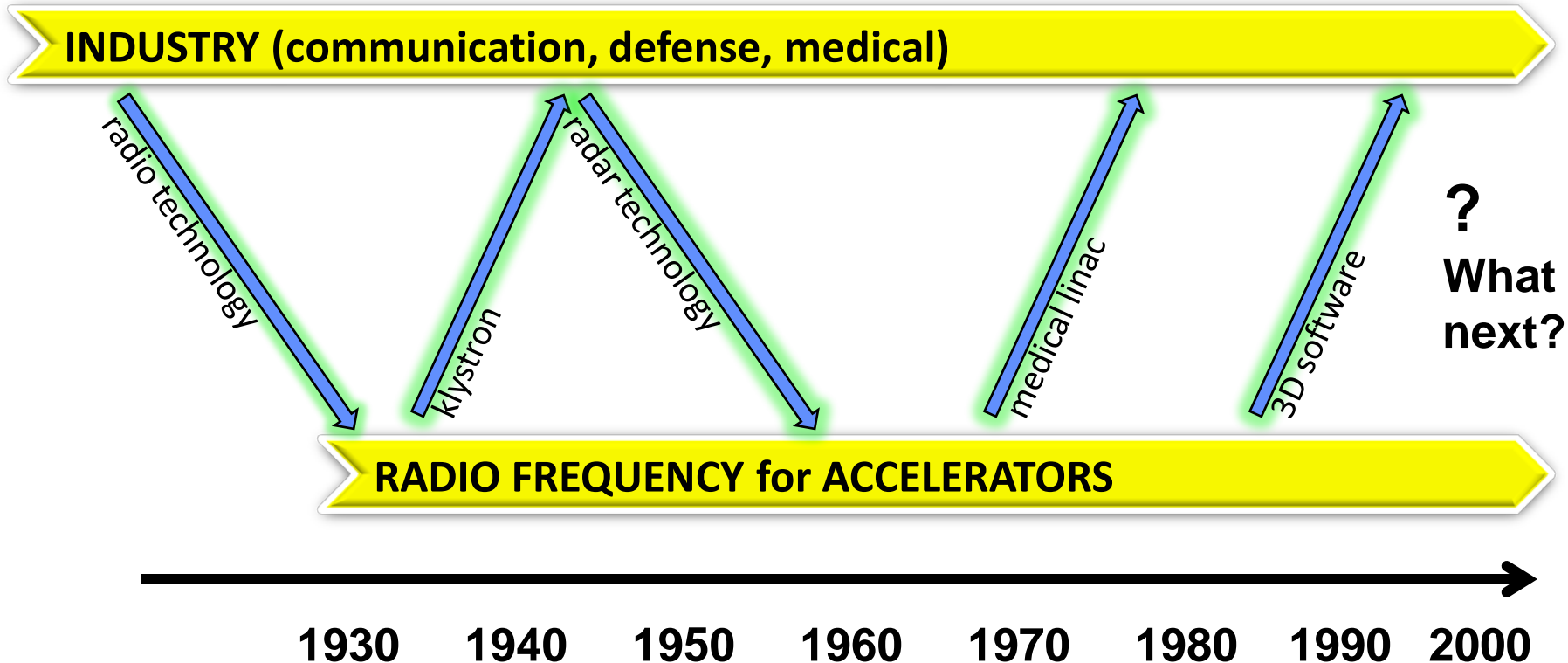
CST offers a wide range of software products to address simulation challenges in the core markets [microwaves & RF](#), [EDA & electronics](#), [EMC/EMI](#), [charged particle dynamics](#), and [statics & and low frequency](#).

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®.





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 a collaboration frame.

There is now an effort (by EU and individual governments) to strengthen the links between these 2 parallel lines → if done correctly, this can be only beneficial to both worlds!

2. The anatomy

For Radio-Frequency in a particle accelerator we mean a system intended to transfer energy to a beam of charged particles by interaction with an electric field oscillating at RF frequency.

What we call "RF system" now generally includes all what is between the wall plug and the beam of particles, i.e.:

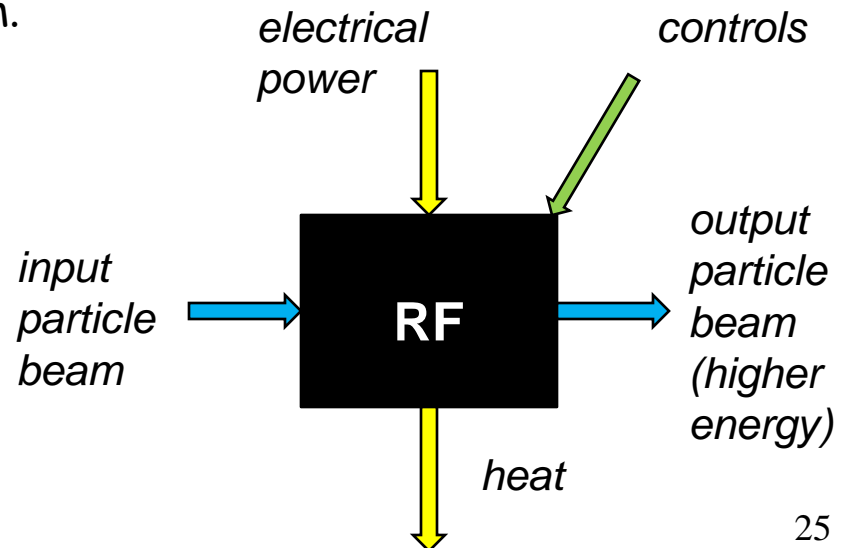
- The RF power generation system;
- The power transport and the coupler to the accelerating cavity;
- The accelerating cavit(es);
- All stabilizing loops around this system.

An RF system can be considered as a black box with 3 inputs:

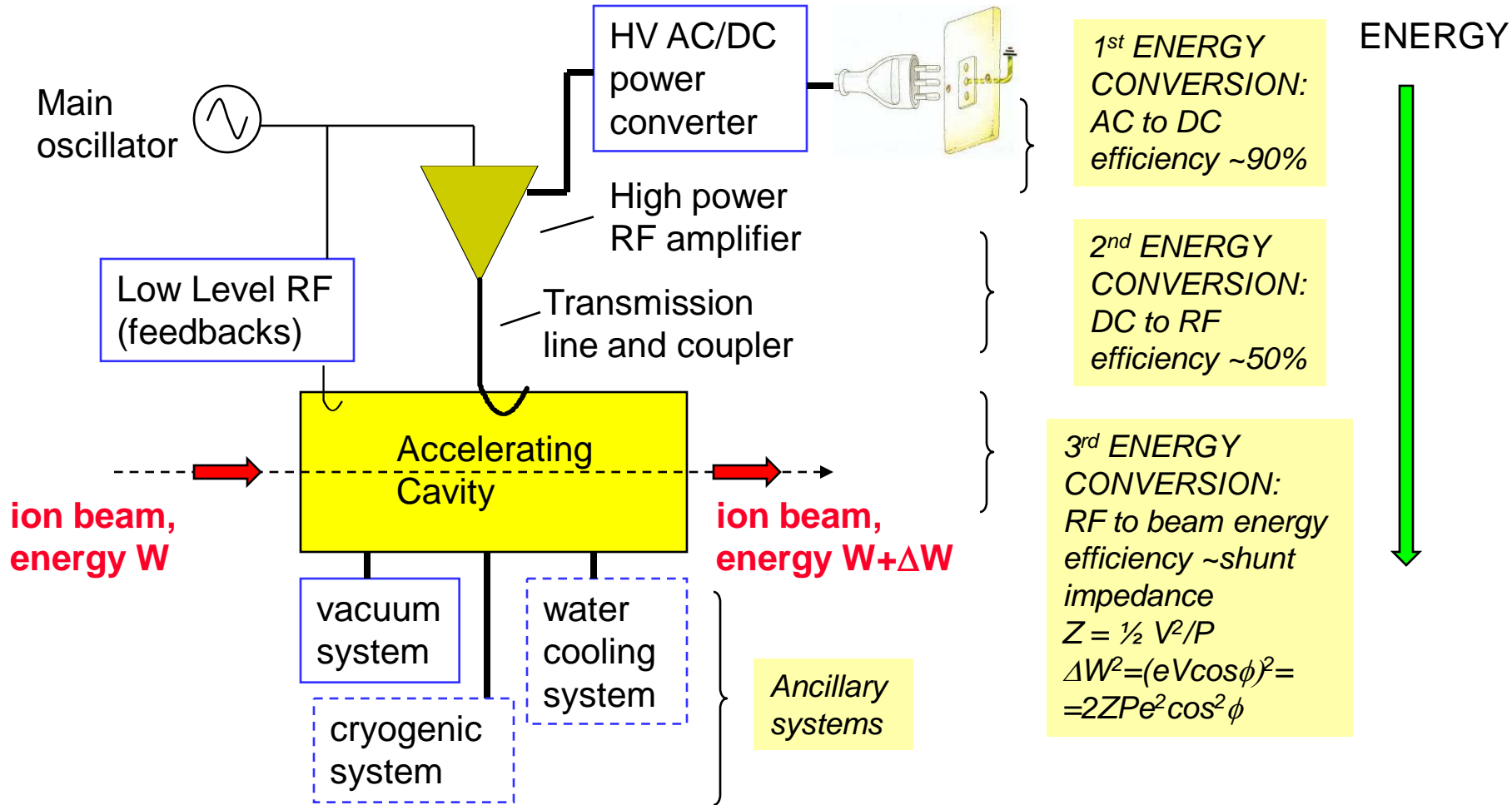
1. Electrical power
2. Controls
3. Input particle beam

and 2 outputs:

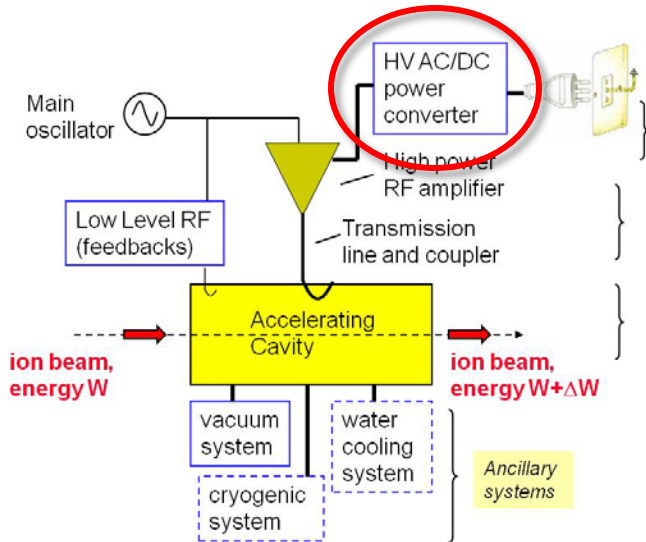
1. Output particle beam
2. Heat (+radiation)



Looking inside the black box: RF building blocks



Radio Frequency is the art of converting energy towards a charged particle beam, with maximum efficiency, minimum installation cost, preserving beam intensity and quality. 26

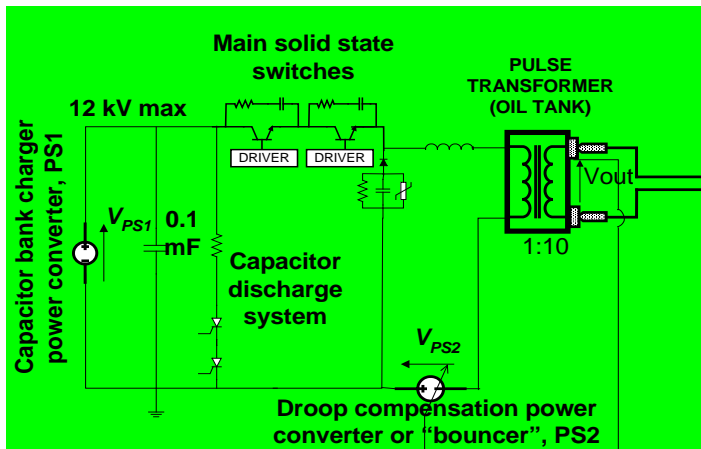


The Power Converter

Is not properly “RF” (sometimes under the responsibility of other groups) but is an essential ingredient for the reliability of the RF system (high voltages!)

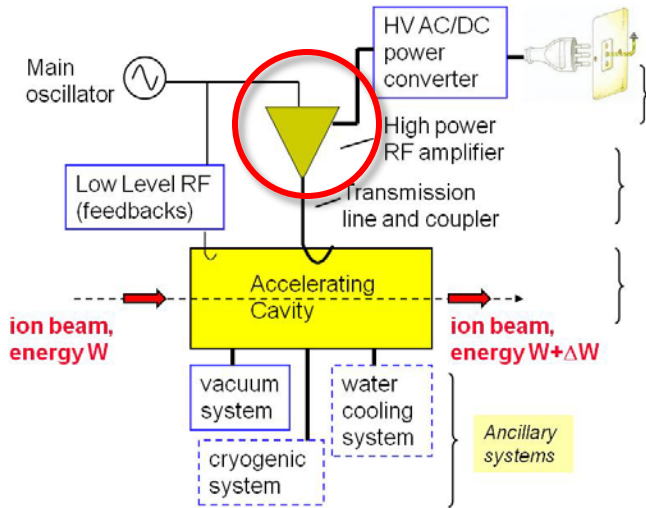
Made of rectifiers + HV transformer + energy storage when pulsed (can be a PFN).

If pulsed and HV, called “modulator”.



Topology and layout of the Linac4 modulator

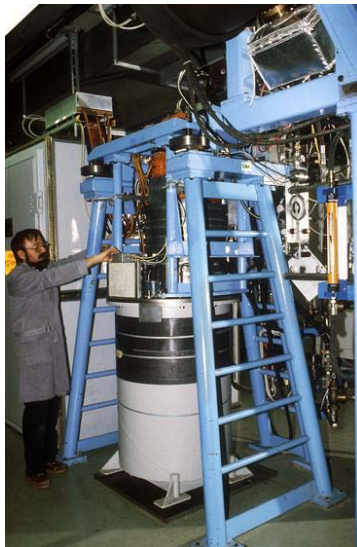




The RF Amplifier

Usually an amplifier chain (sometimes called “transmitter”).

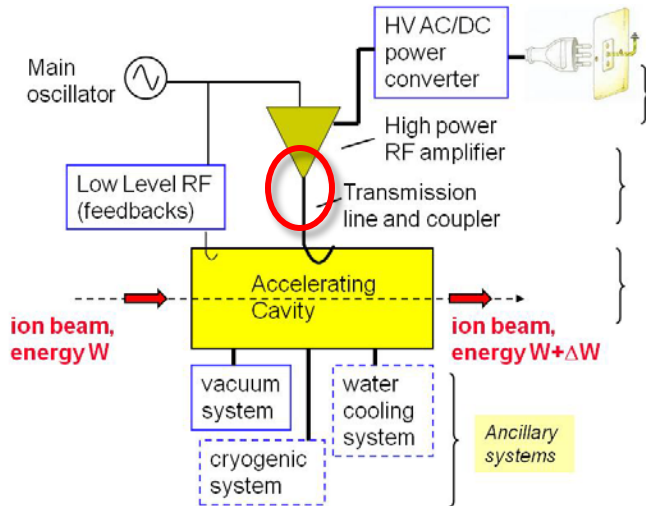
Provides the RF power, is based on an active device: RF tube (tetrode or triode), klystron or RF transistor (solid state).



The CERN LIL klystron (3 GHz)



The CERN Linac1 triode amplifiers (2 MW, 202 MHz) in a photo of 1959

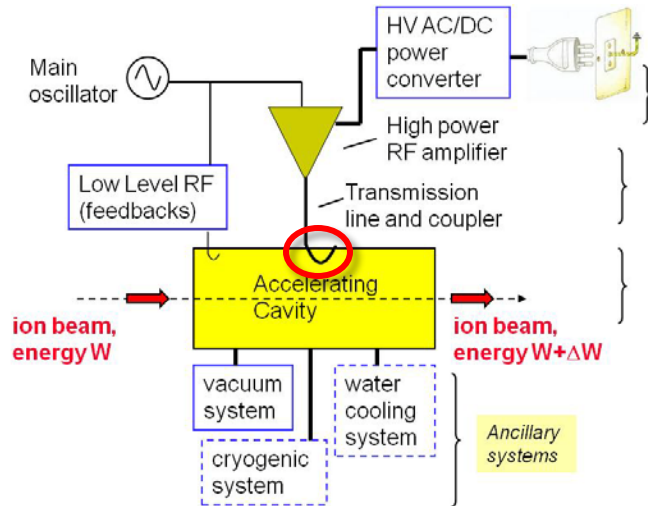


The transmission line

Power has to be transported to the final load without reflections (matching), with minimum loss and reliably (no arcs!). Coaxial (rigid or cable) or waveguide.

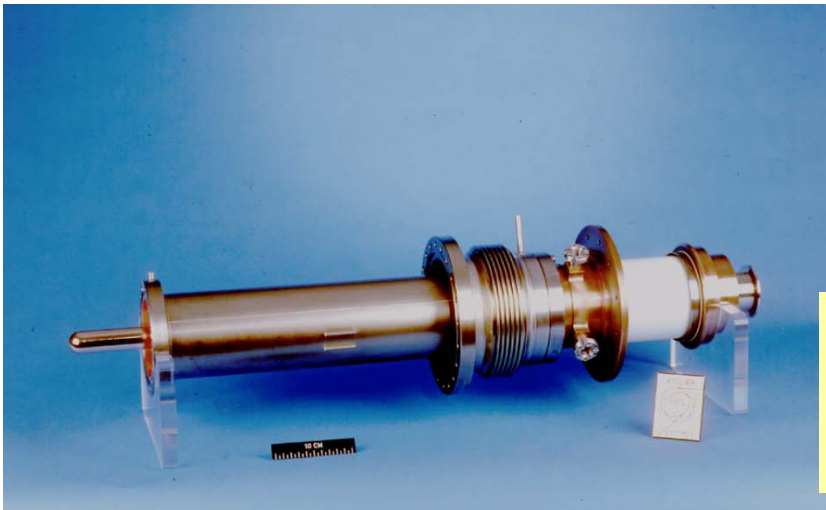


Rigid coaxial lines for the CERN TW 400 MHz RF system at the SPS

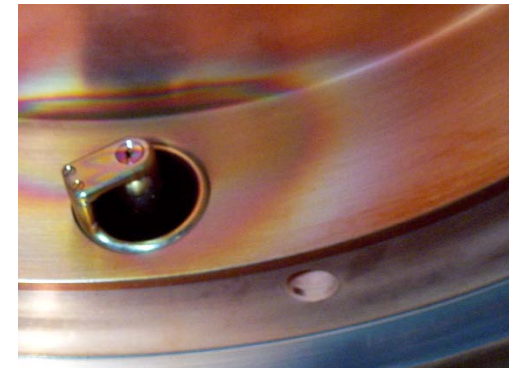


The power coupler

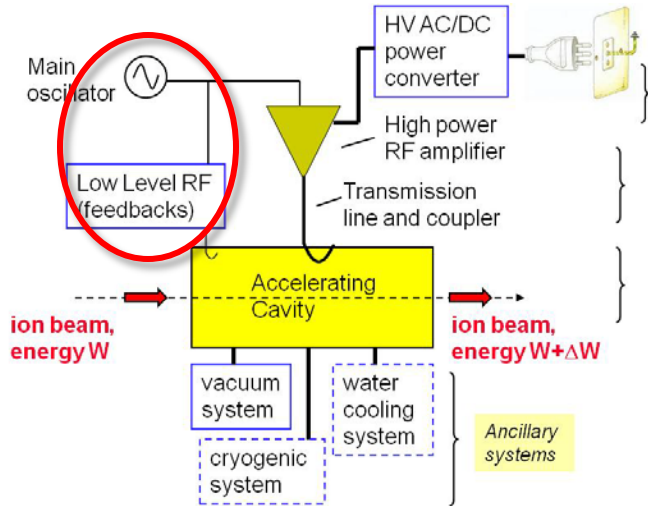
Critical element, needs to transform the cavity impedance into the load impedance of the line (or into any wanted impedance), separating the vacuum in the cavity from the air (or dielectric) in the line (window). Can be a loop, an antenna or an iris to a waveguide.



Antenna coupler for the LEP2 superconducting cavities.



Small loop coupler to a 400 MHz buncher after 15 years of operation, with traces of multipactoring



The Low Level RF

Electronics aimed at stabilizing the voltage in the cavity against perturbations coming from inside the amplifier chain, from the cavity and from the beam.

Can be analog, analog/digital or digital.

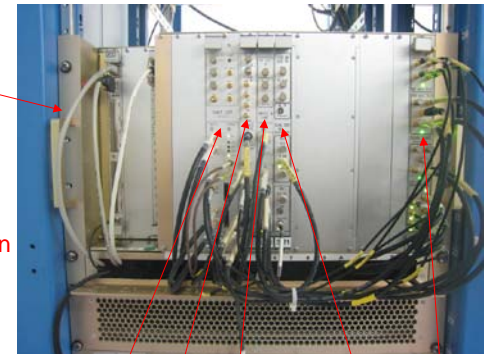
The LHC LLRF (overview of one unit)



Cavity Controller VME crate

Antenna calibration and 100 mW pre-driver

RF cable splitting



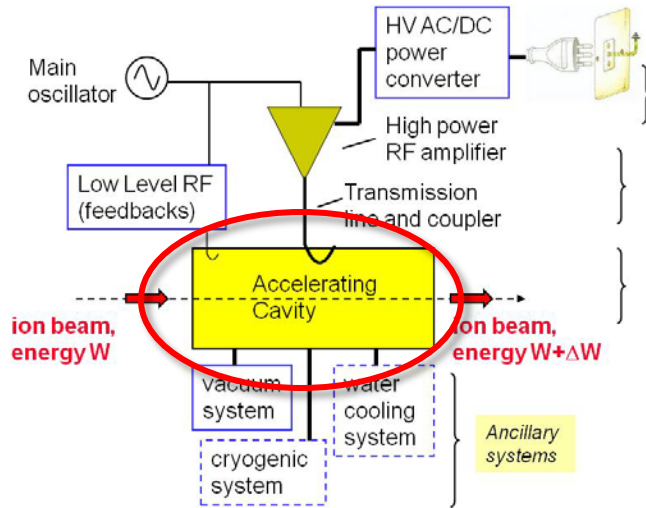
Tuner Control

RF Modulator

Switch&Limit

Conditioning DDS

Clock Distri



The accelerating cavity

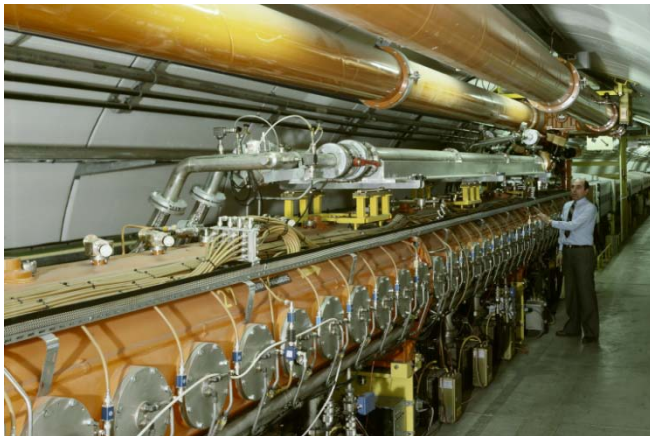
The heart of the system.

Accumulates electric energy in a series of gaps, with minimum power loss.

Essential is the synchronism between field and particles → the particles have to be at the right place at the right moment.

Can have a variable frequency (to follow variation in revolution frequency of the particles).

An RF cavity is a multidisciplinary object: integrates beam dynamics (sequence and position of gaps), electromagnetic design (E-field configuration), mechanical design (construction, joining techniques), vacuum, thermo mechanical issues (cooling or cryogenics),...



The CERN SPS accelerating cavity

3. The H factor



Radio-frequency is:

- a theoretical and **intellectually challenging** subject (usually attracting bright people...),
- an activity very **close to hardware and workshops** (usually counting on very good technical people...),
- a field where **team work** is vital !

These elements have allowed to shape the key factor for the success of the RF technology:

The H = HUMAN factor → **the RF people.**



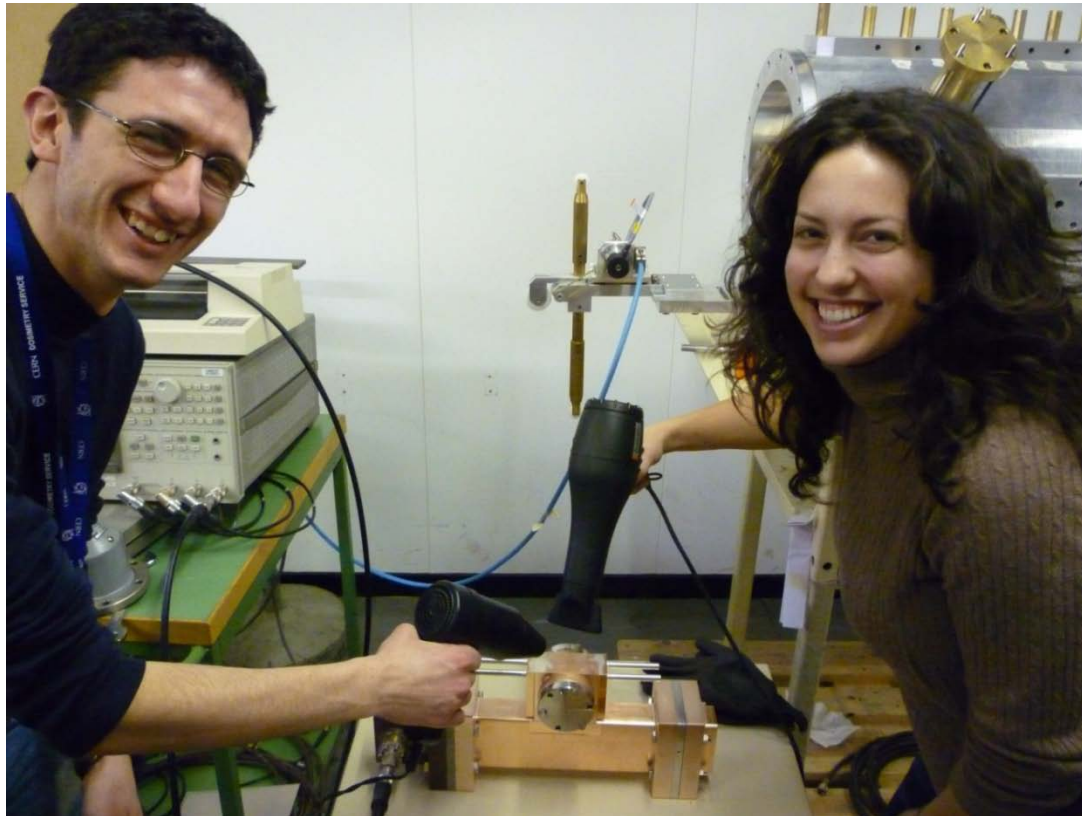
The technology shapes the people... and
the people shape the technology.

And all around the world, RF teams have
something different...

Pride for the result (hardware with a large intellectual content!)



Innovative ideas (sometimes called “bricolage”, but RF is the science of “creative bricolage”!)



CAS

RF means also...



Very specialized workshops...

... with a special atmosphere



Colossal parties...



Pantagruelian barbecues



**We are here also to celebrate:
82 years of history
and the 4th RF CAS school...**

**... and we have to
take the chance to
cheer and toast to
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