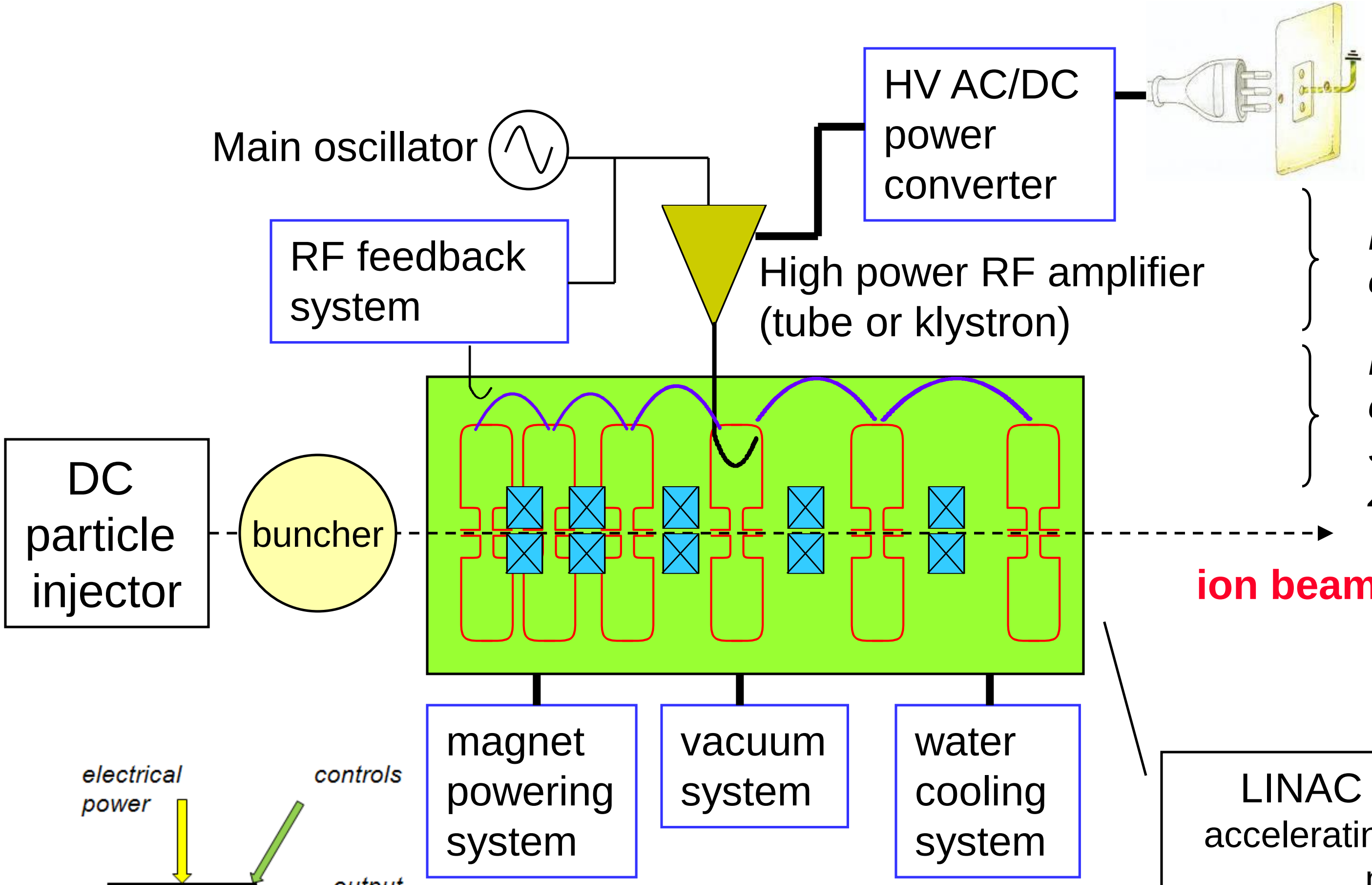
HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

CERN

Module 4
Anatomy of a linear accelerator
Linac technologies
RF parameters and measurements

Linac building blocks



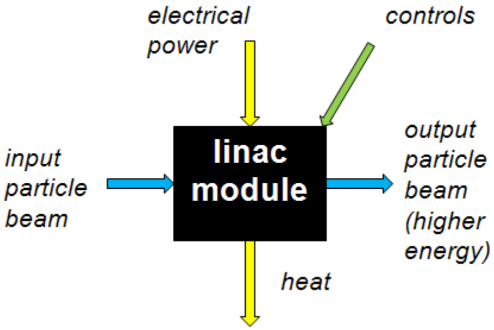
AC to DC conversion efficiency ~90%

DC to RF conversion efficiency ~50%

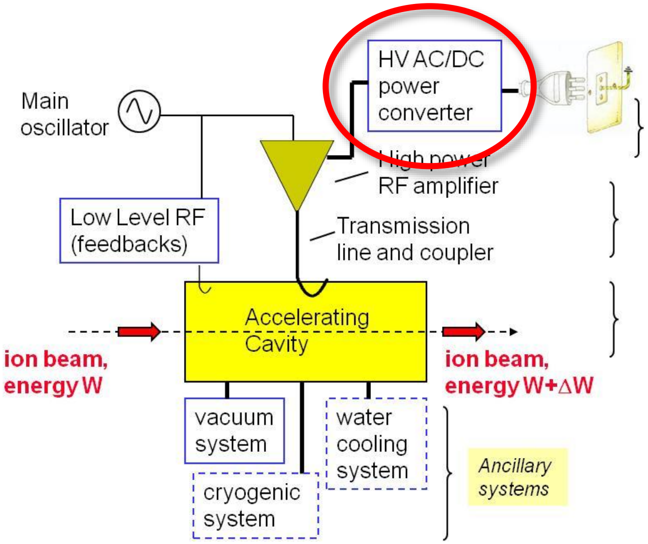
RF to beam voltage conversion efficiency = SHUNT IMPEDANCE ZT^2 ~ 20 - 60 MΩ/m

ion beam, energy W

LINAC STRUCTURE
accelerating gaps + focusing magnets
designed for a given ion, energy range, energy gain



Anatomy - 1

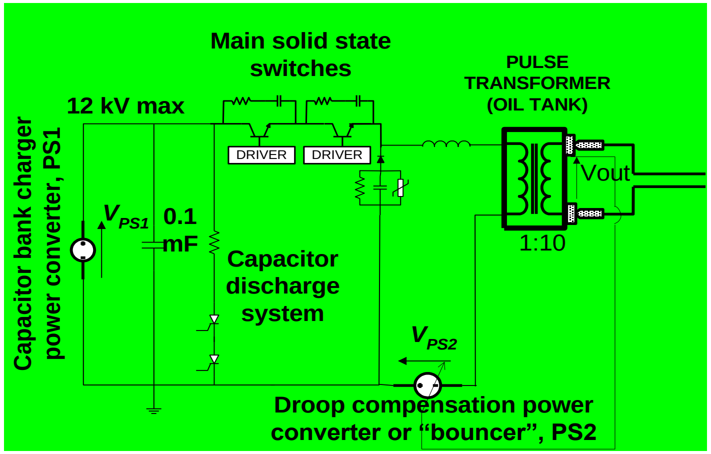

Main oscillator
HV AC/DC power converter
High power RF amplifier
Low Level RF (feedbacks)
Transmission line and coupler
Accelerating Cavity
ion beam, energy W
ion beam, energy W+ΔW
vacuum system
water cooling system
cryogenic system
Ancillary systems

The Power Converter

An essential ingredient for the reliability (high voltages!), stability (noise) and cost of a linac!

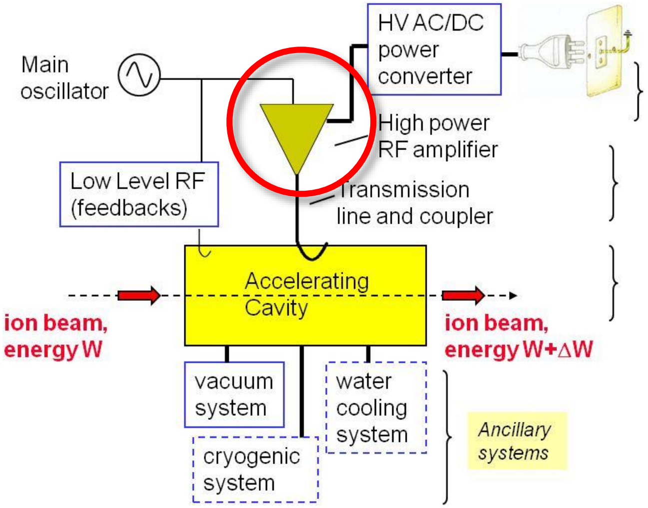
Made of rectifiers + HV transformer + energy storage when pulsed (can be a PFN).

If pulsed and HV, called “modulator”.



Topology and layout of the Linac4 modulator

Anatomy - 2



The RF Amplifier

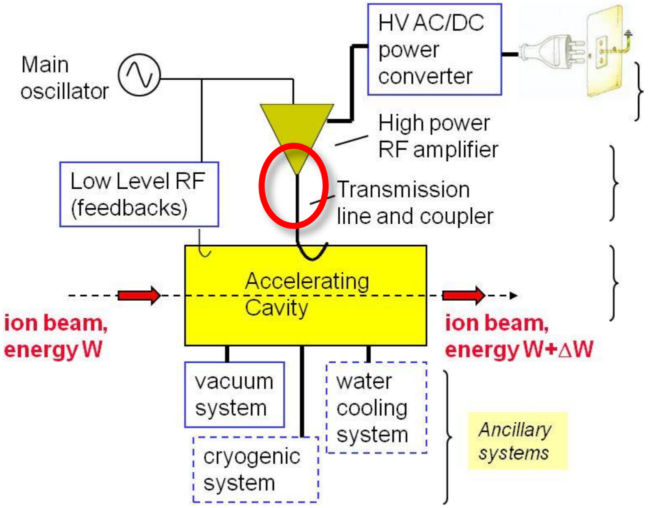
Usually an amplifier chain (sometimes called “transmitter”).

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)

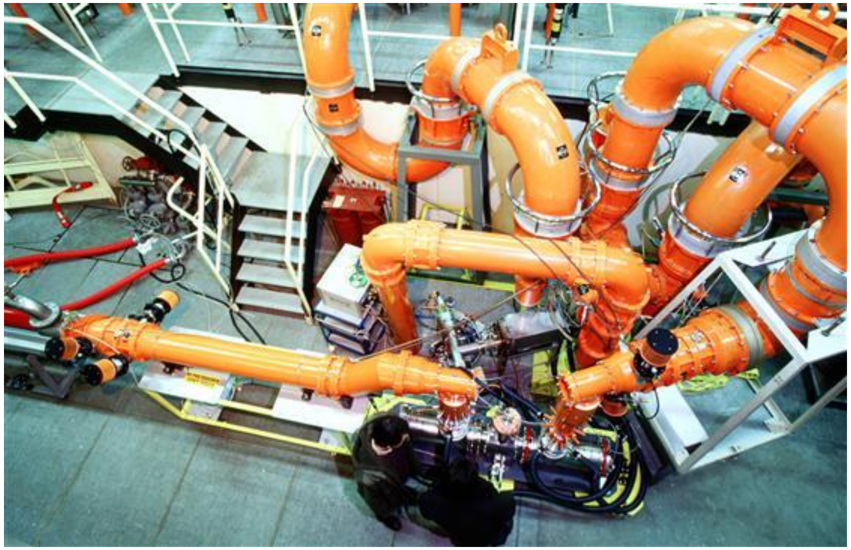
The CERN Linac1 triode amplifiers (2 MW, 202 MHz) in a photo of 1959

Anatomy – 3



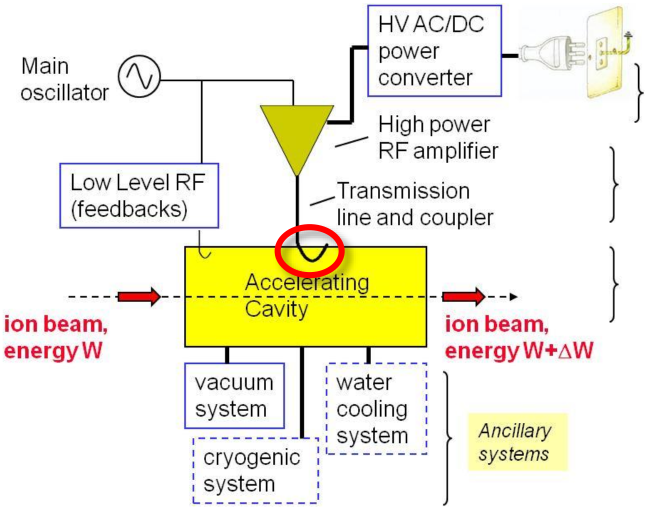
The transmission line

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.



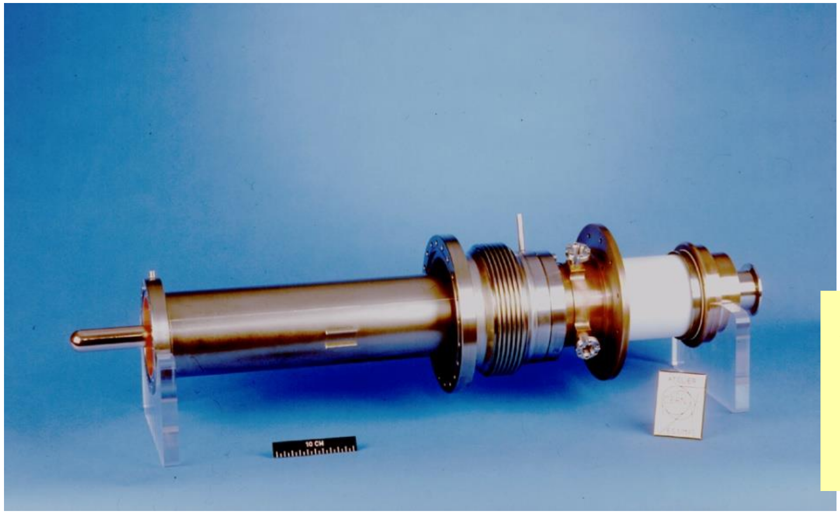
Rigid coaxial lines for the CERN TW 400 MHz RF system at the SPS

Anatomy - 4

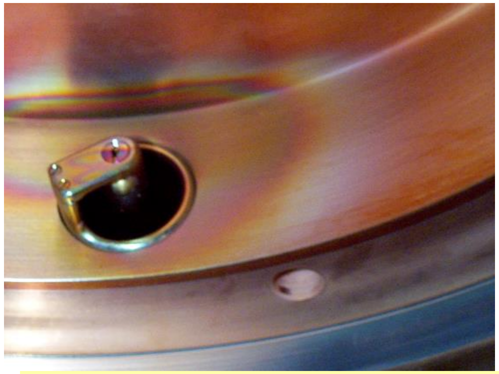


The power coupler

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.

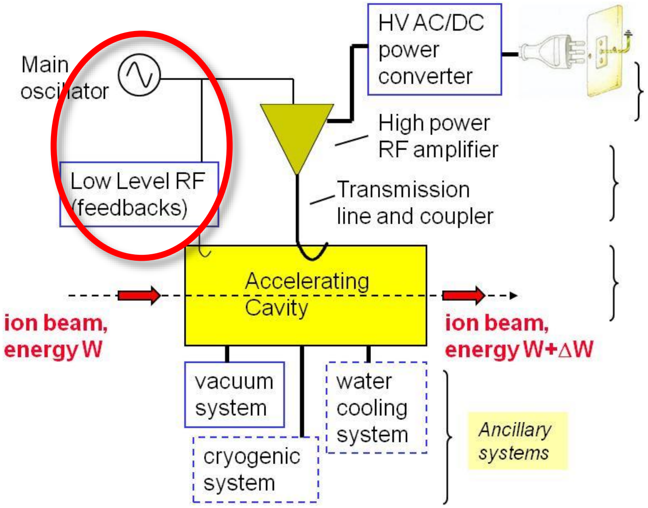


Antenna coupler for the LEP2 superconducting cavities.



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

Anatomy - 5

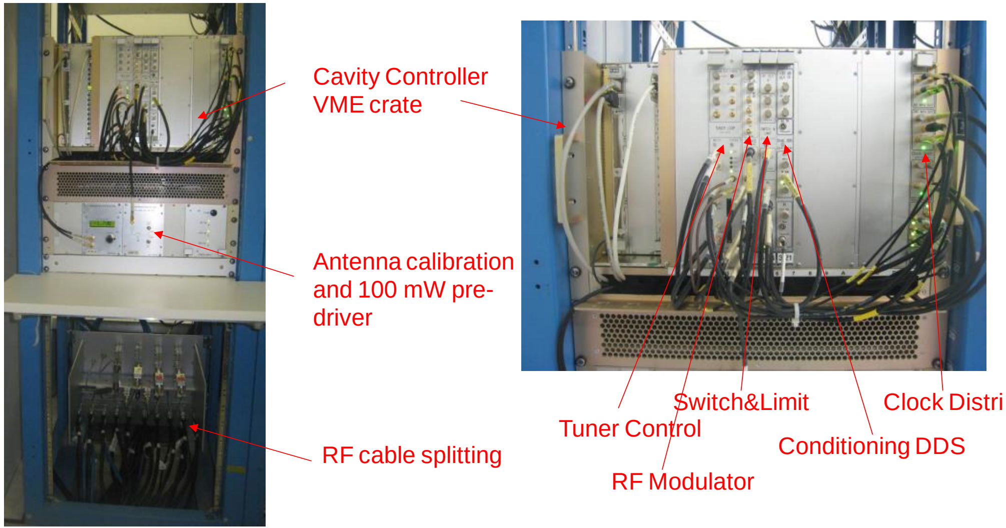


The Low Level RF

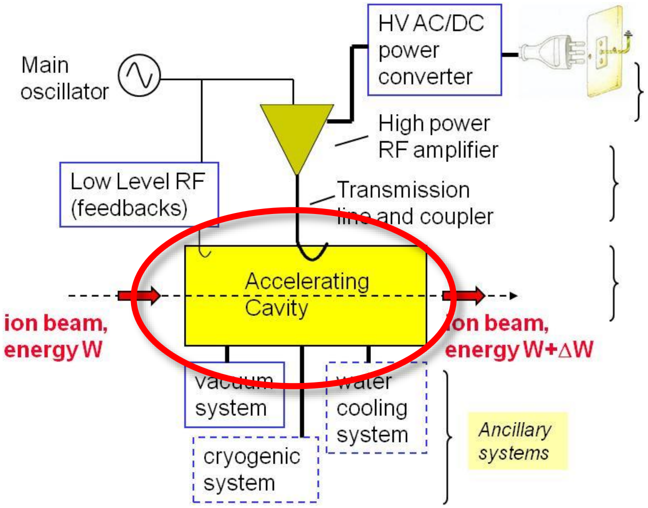
Electronics aimed at stabilizing the voltage in the cavity against perturbations coming from inside the amplifier chain, from the cavity and from the beam.

Can be analog, analog/digital or digital.

The LHC LLRF (overview of one unit)



Anatomy - 6



The CERN Linac2 accelerating cavities

The accelerating cavity

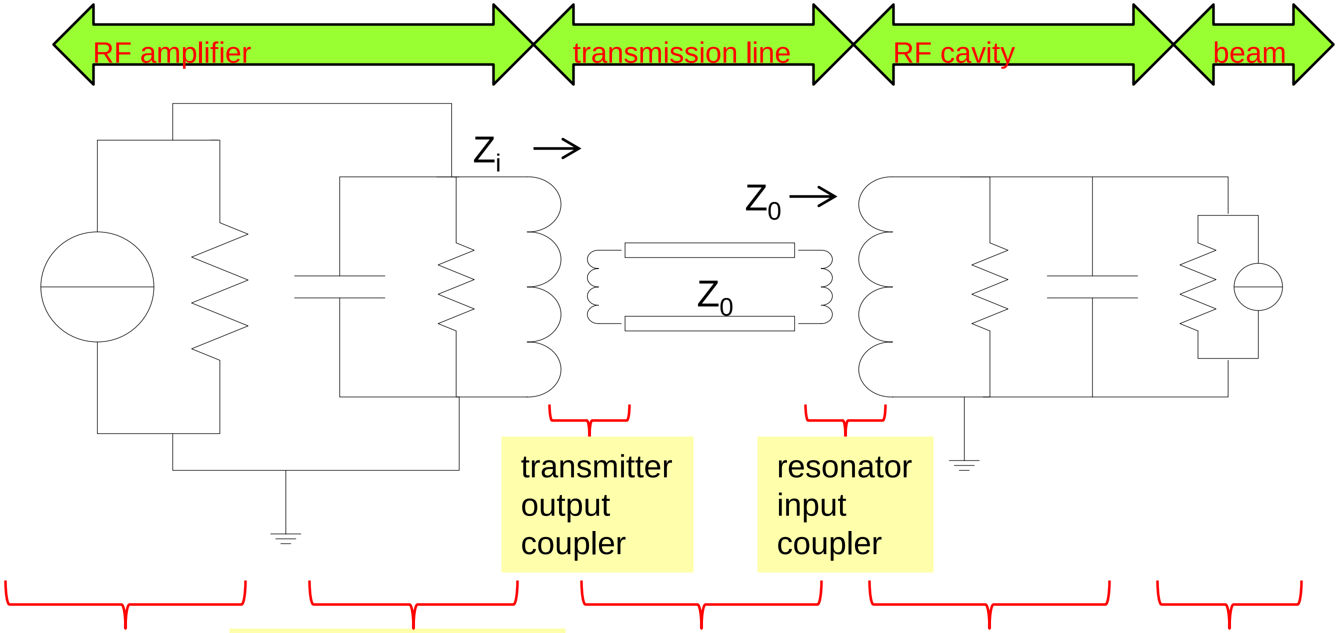
The heart of the system.
Accumulates electric energy in a series of gaps, with minimum power loss.
Essential is the synchronism between field and particles → the particles have to be at the right place at the right moment.

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 RF system

A closer insight of what the RF does is given by the equivalent circuit of an amplifier/cavity system

RF is the art of transporting energy by matching impedances



transmitter output coupler

resonator input coupler

active unit (tube or klystron): current generator with internal impedance

output resonator of the transmitter (klystron): filters higher order harmonics and coupes to the line

transmission line

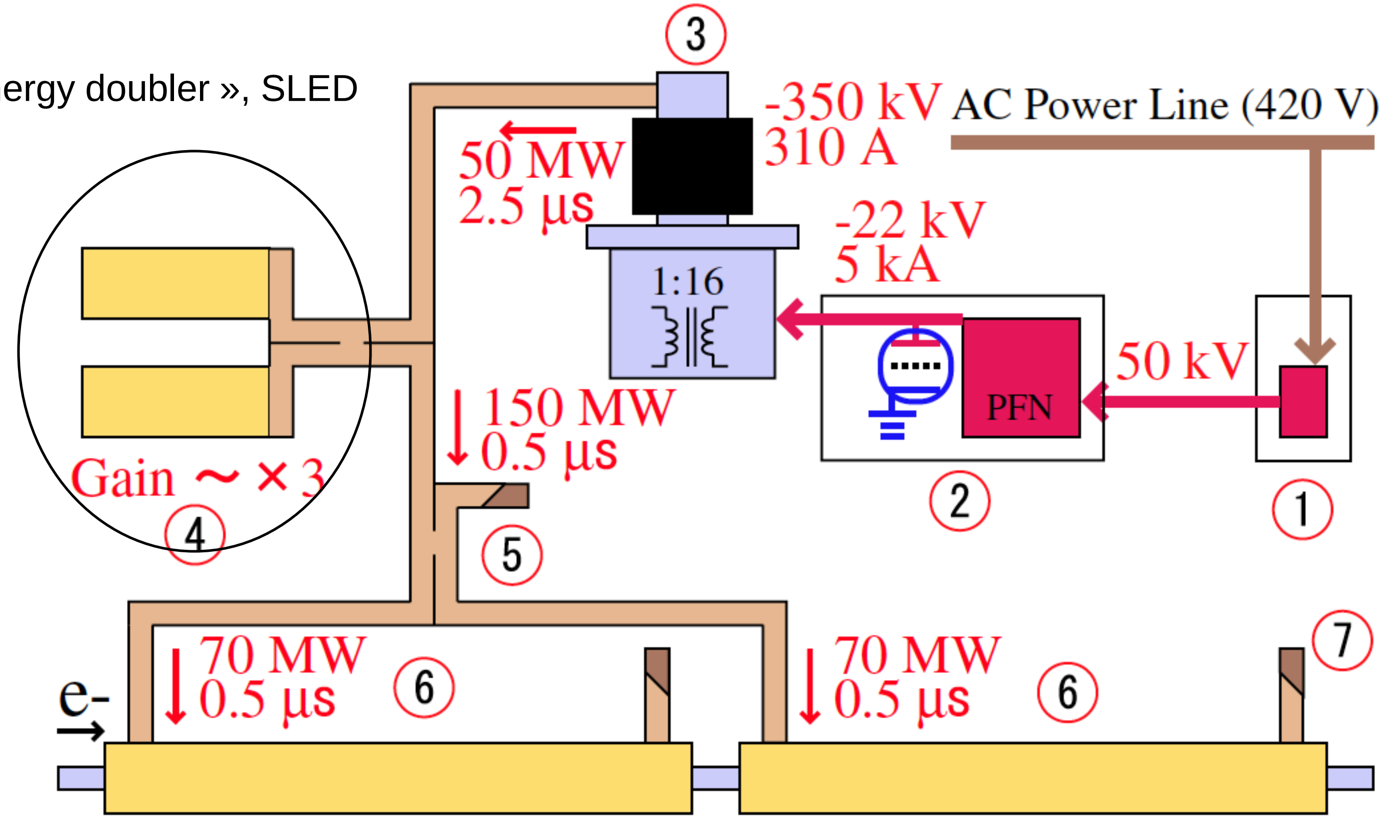
Cavity resonator

Beam: additional resistance (power given to the beam) + current generator out of phase

Electron linac building blocks

TSUMORU SHINTAKE *et al.*

« Energy doubler », SLED



Linac Technologies

Particle production – the sources

Electron sources:

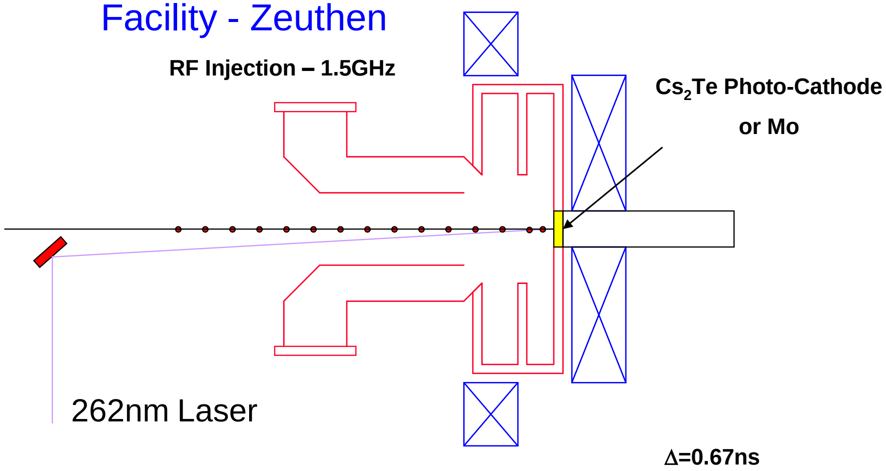
give energy to the free electrons inside a metal to overcome the potential barrier at the boundary. Used for electron production:

- thermoionic effect
- laser pulses
- surface plasma

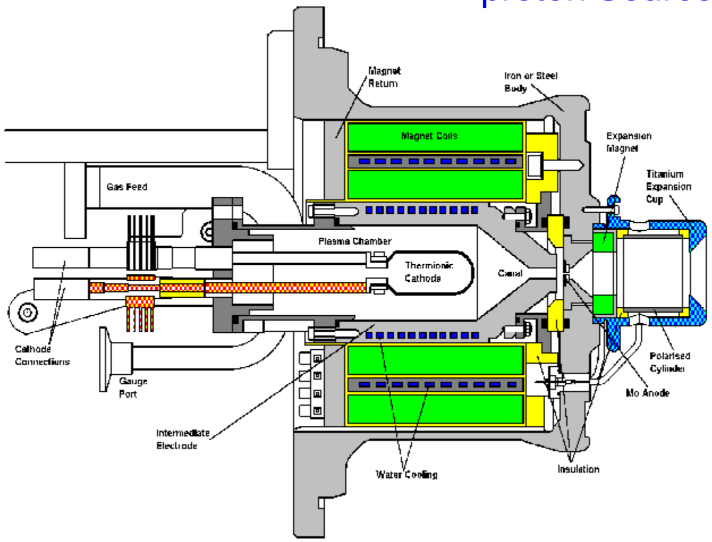
Ion sources:

create a plasma and optimise its conditions (heating, confinement and loss mechanisms) to produce the desired ion type. Remove ions from the plasma via an aperture and a strong electric field.

Photo Injector Test Facility - Zeuthen



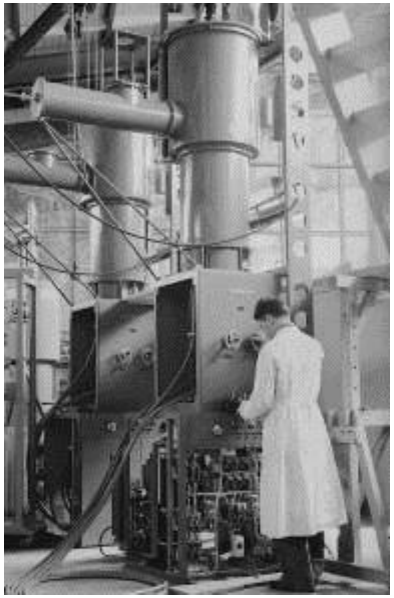
CERN Duoplasmatron proton Source



RF and construction technologies

- → Type of RF power source depend on frequency:
  - ☞ Klystrons (>350 MHz) for electron linacs and modern proton linacs. RF distribution via waveguides.
  - ☞ RF tube (<400 MHz) or solid state amplifiers for proton and heavy ion linacs. RF distribution via coaxial lines.
- → Construction technology depends on dimensions (→on frequency):
  - ☞ brazed copper elements (>500 MHz) commonly used for electron linacs.
  - ☞ copper or copper plated welded/bolted elements commonly used for ion linacs (<500 MHz).

3 GHz klystron (CERN LPI)



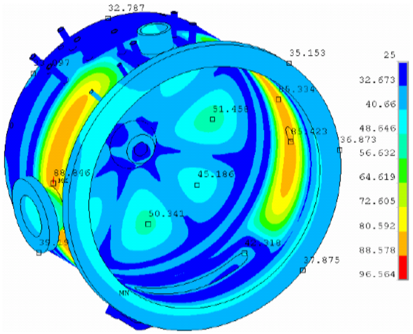
200 MHz triode amplifier (CERN Linac3)

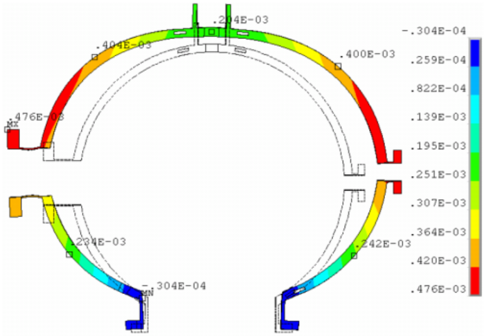
Construction technologies

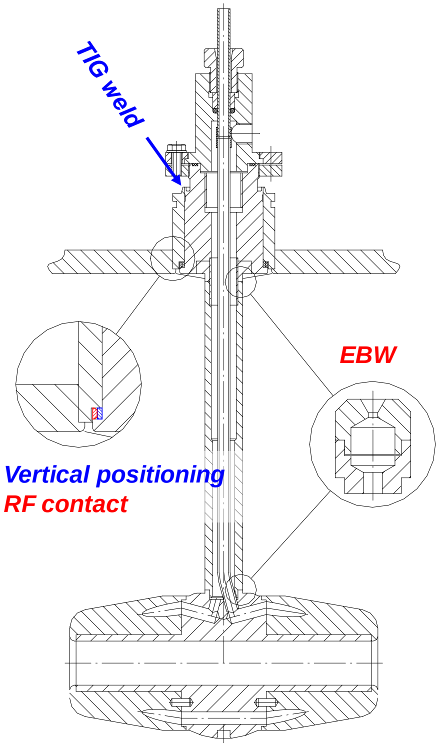
Linac accelerating structure:

Set of parts joined together; needs to have:

- A well defined vacuum envelope (no trapped volumes, special vacuum joints)
- A well defined RF envelope (no leaking RF, good RF contacts between parts)
- A stable mechanical structure under vibrations and thermal deformations
- An effective cooling of the heat produced by the RF.



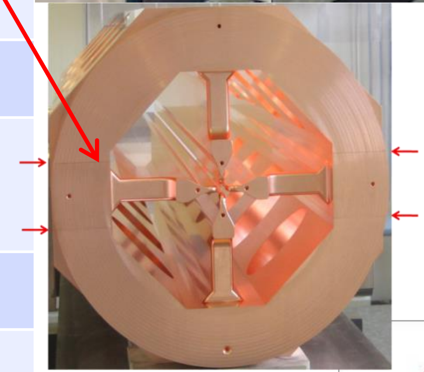


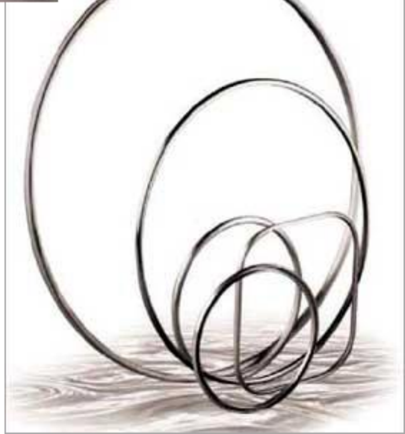


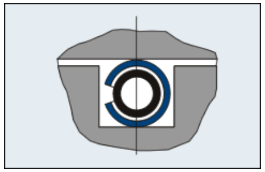
In most of the cases,
it is on the mechanical construction that you will win or lose your linac project…

Joining techniques

		vacuum	RF
Metal to metal	EB welding	ok	ok
	Brazing	ok	ok
	TIG welding	ok	ok
Gaskets	O-ring	ok (lifetime)	no
	Conflat	ok	no (s. steel)
	Wires (Al, In, Au, Cu,..)	ok (difficult)	ok
	Spring cont.	no	ok (power)
	C-seals	ok	ok
Additonal	Shrink-fitting	no	dangerous
	Knife-edge	dangerous	ok

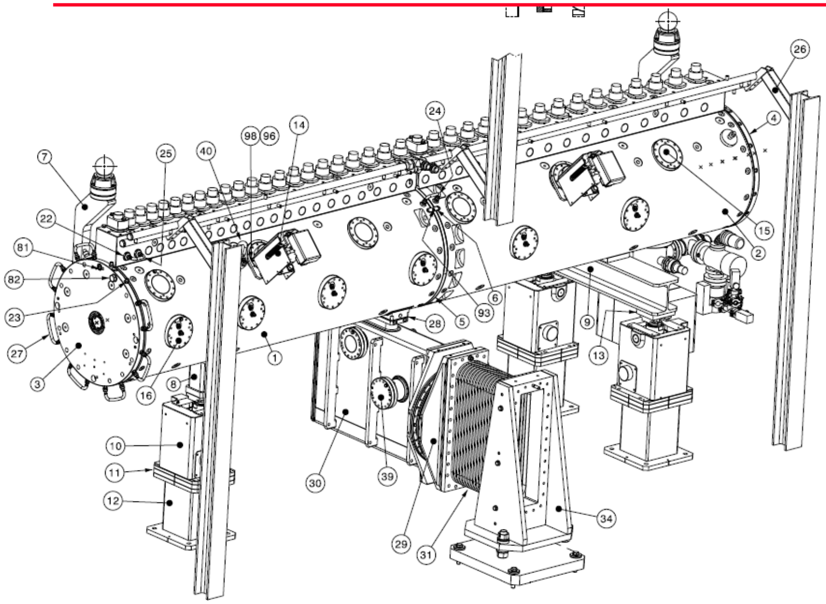


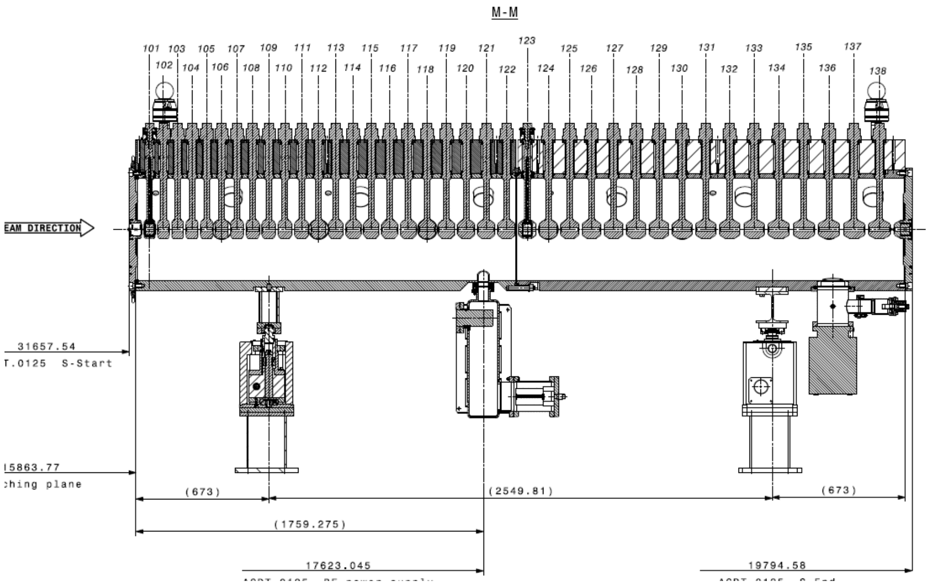


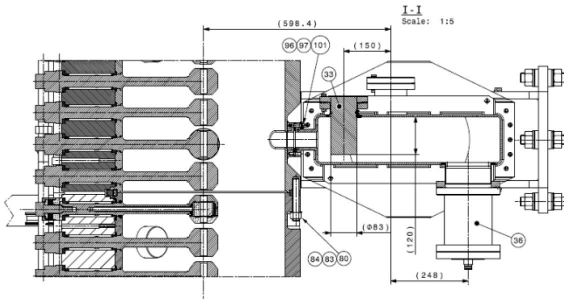


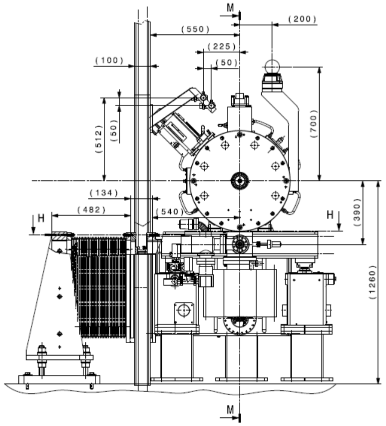
EB=Electron Beam
TIG=Tungsten Inert Gas
C-seals also known as Helicoflex

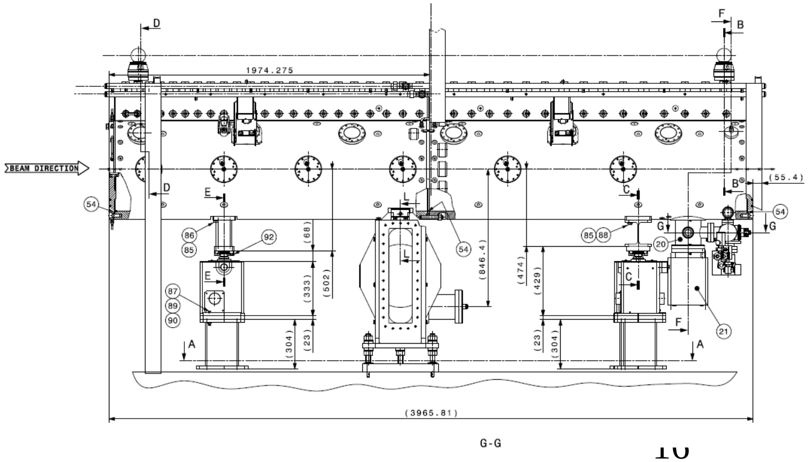
Example: Linac4 DTL Tank1



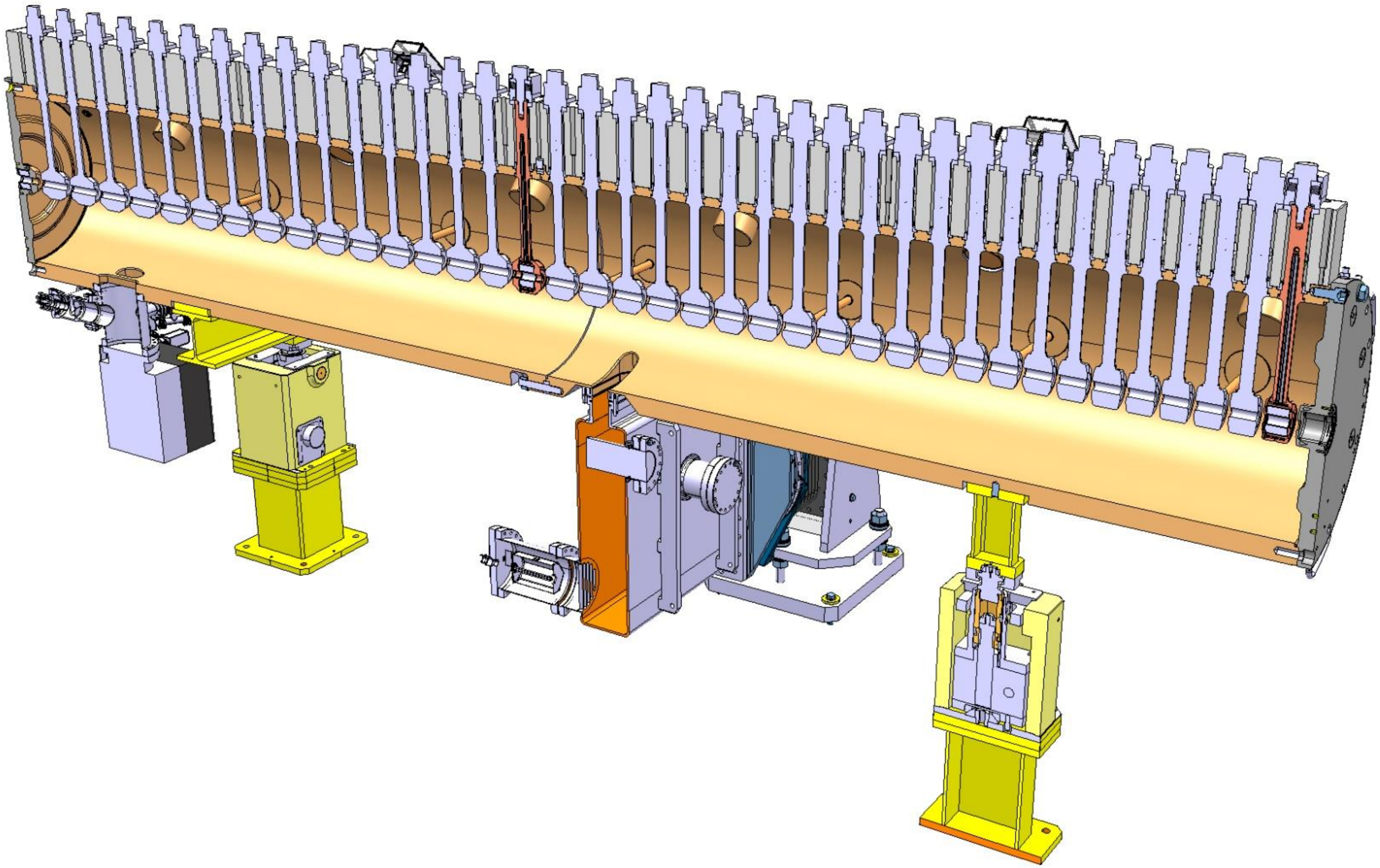






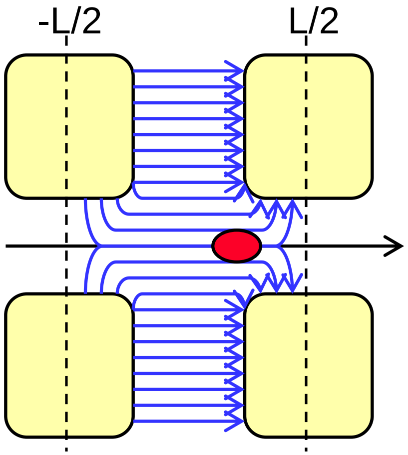


a puzzle of several thousand elements…



Important RF parameters (and how to measure them…)

Energy gain



Particle crossing an RF gap in a linac cell of length L:

E-field is $E_z(z,t) = E(z)\cos(\omega t + \varphi)$

The shape of E_z depends on gap length and aperture radius

Voltage is $V_0 = \int_{-L/2}^{L/2} E(z)dz = E_0 L$

E_0 mean field

Energy gain by a particle crossing the gap at phase ϕ is:

$$\Delta W = e\int_{-L/2}^{L/2} E(z)\cos[\omega t(z)+\varphi)]dz = e\int_{-L/2}^{L/2} E(z)[\cos\omega t\cos\varphi - \sin\omega t\sin\varphi]dz = eV_0 T\cos\varphi$$

with a Transit Time Factor defined as:

$$T = \frac{\int_{-L/2}^{L/2} E(z)\cos\omega t(z)dz}{\int_{-L/2}^{L/2} E(z)dz} - \tan\varphi\frac{\int_{-L/2}^{L/2} E(z)\sin\omega t(z)dz}{\int_{-L/2}^{L/2} E(z)dz} \underset{\uparrow}{=} \frac{\int_{-L/2}^{L/2} E(z)\cos\omega t(z)dz}{\int_{-L/2}^{L/2} E(z)dz} = \frac{1}{V_0}\int_{-L/2}^{L/2} E(z)\cos\omega t(z)dz$$

For E(z) even function of z

$$\Delta W = eE_0TL\cos\varphi$$

« Panofsky equation » very simple, but the physics is in the transit time factor!

Transit time factor

$$\Delta W = eE_0 TL\cos\varphi$$

design parameter, (see Module 6)

cell length, βλ or βλ/2

from frequency, gap geometry and particle velocity

synchronous phase angle, from beam dynamics (longitudinal stability)

$$T = \frac{\int_{-L/2}^{L/2} E(z)\cos\omega t(z)dz}{\int_{-L/2}^{L/2} E(z)dz}$$

energy gain by a particle in the middle of the gap at t=0

energy gain by a particle crossing the gap with infinite velocity at t=0

The Transit Time Factor T tells us how much of the E-field that we have provided on the gap has been really seen by a particle moving at velocity v=βc.
Is the ratio between 2 integrals (0 ≤T ≤ 1)

Neglecting the increase in velocity in the gap:

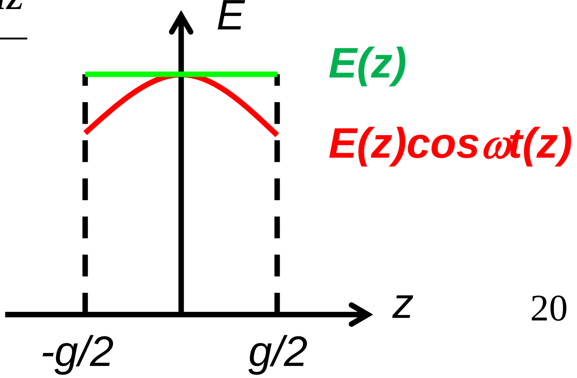
$$\omega z = \frac{2\pi c}{\lambda}\frac{z}{\beta c} = \frac{2\pi z}{\beta\lambda}$$

$$T = \frac{\int_{-L/2}^{L/2} E(z)\cos(2\pi z/\beta\lambda)dz}{\int_{-L/2}^{L/2} E(z)dz}$$

For the simplest case $E(z)=E_0$ (-g/2, g/2):

$$T = \frac{\sin(\pi g/\beta\lambda)}{\pi g/\beta\lambda}$$

T is a characteristic of your design; it can be easily calculated by the RF design codes



Shunt Impedance

Design of an accelerating system → goal is to maximize acceleration ΔW for a given power delivered to the cavity P_c. Can we define a **figure of merit** to compare different designs?

We define a « shunt impedance » Z as $Z = \frac{V_0^2}{P_c}$; exactly twice the shunt resistance in the equivalent parallel circuit

The figure of merit is (considering maximum acceleration at ϕ=0 and taking the square of the energy gain in volts, to give consistancy to the units):

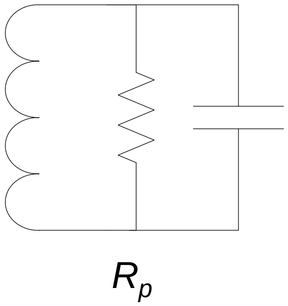
$$\frac{\Delta W^2}{e^2 P_c} = \frac{(eE_0TL)^2}{e^2 V_0^2 / Z} = Z\frac{(E_0TL)^2}{(E_0L)^2} = ZT^2$$

$$ZT^2 \quad [\Omega]$$

$$ZT^2 / L \quad [\Omega / m]$$

ZT^2 is the **effective shunt impedance**, depends only on the geometry (and on RF frequency and particle velocity). Unit is ohms (usually MΩ, or MΩ/m if referred to the unit length). Can be easily calculated by computer codes, and then used to calculate the cavity power and the final power efficiency:

$$P_c = \frac{V_0^2}{Z} = \frac{(E_0L)^2}{Z} = \frac{(\Delta W)^2 / \cos^2\varphi}{ZT^2}$$



$$R_p = \frac{1}{2} Z$$

ATTENTION!!!
Usually in linacs we use Z, while for other RF systems and in other literatures is used R_p: difference by a factor 2 !

Power efficiency

$$efficiency = \frac{P_b}{(P_b + P_c)} \cong \frac{P_b}{P_c} = \frac{I\,\Delta W\,ZT^2}{\Delta W^2 / \cos^2\varphi} = \frac{I\,ZT^2 \cos^2\varphi}{\Delta W / e} = \frac{I\,ZT^2 \cos\varphi}{(E_0 T) L} = \frac{I}{E_0 T}\frac{ZT^2}{L}\cos\varphi$$

$$efficiency = \frac{I}{E_0 T}\frac{ZT^2}{L}\cos\varphi$$

Main design parameters: beam current and effective gradient

synchronous phase

Shunt impedance per unit length

For a normal conducting linac with low beam loading, the RF power efficiency (proportional to the wall plug efficiency) is proportional to peak beam current, shunt impedance, and cosine of the synchronous phase. It is inversely proportional to the effective gradient → long linacs with low gradient have a higher efficiency (but higher construction cost…)

The 3 cavity parameters

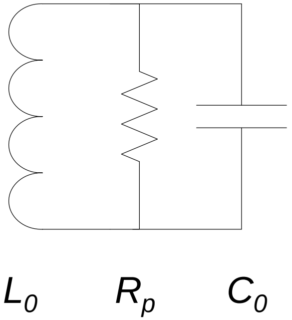
A resonator (= a mode in a linac accelerating cavity) is defined by a set of 3 parameters.

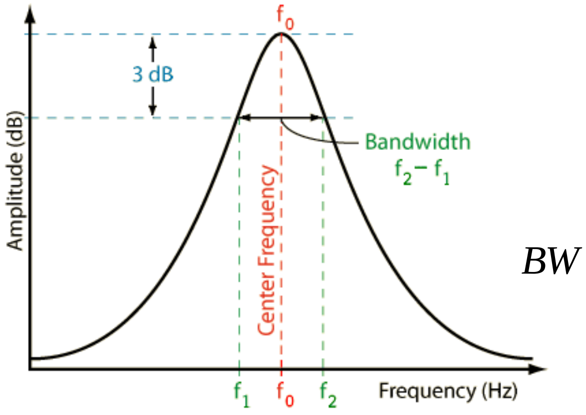
They can be:

(Capacitance, Inductance, Resistance)

(Frequency, Q-value, R/Q)

$$f_0 = \frac{1}{2\pi\sqrt{L_0 C_0}} \qquad Q_0 = 2\pi\, f_0 R_p C_0$$





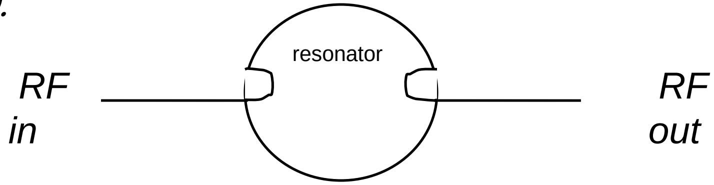
$$R/Q = \frac{1}{2\pi\, f_0 C_0} = \sqrt{\frac{L_0}{C_0}}$$

$$BW[3dB] = \frac{f_0}{Q_0}$$

R/Q is a geometrical parameter, basically tells you the ratio between current and voltage in your system

An RF transmission measurement can easily allow to get (f, Q) from the 3db bandwidth.

(precaution: to measure Q_0: we need a sufficiently low ioupling. If input coupling is too large, is measured the Q loaded (Q_l), given by the parallel of the cavity R and the transformed output impedance of the measurement device).



Measurement of R (R/Q)

The most difficult measurement (and for this reason one usually relies on simulation codes).

1. Direct voltage calibration: $Z = \frac{V_0^2}{P_c}$: we need to measure the power and then the voltage from an X-ray measurement

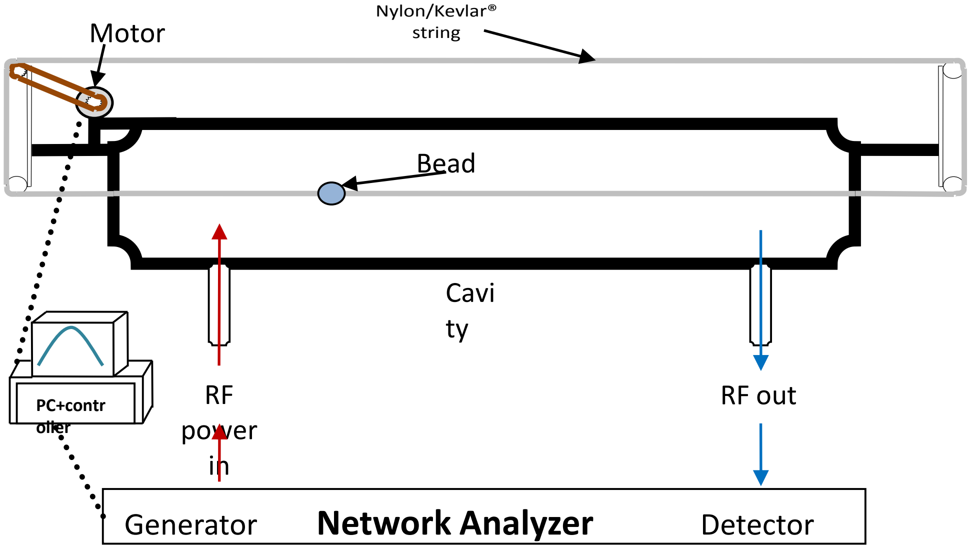
2. Perturbation measurement: $\frac{\Delta f}{f} = \frac{\int_{\Delta V} (\mu H^2 - \varepsilon E^2) dV}{2U} = \frac{1}{2} \frac{\Delta U}{U}$

a small perturbation (introduction of an object in a resonant cavity) shifts the frequency by one half of the ratio between change in magnetic minus electric energy and the total stored energy → knowing ΔU it is possible to calculate U!!!

R/Q:

$$Q = \frac{\omega U}{P} \qquad \frac{R}{Q} = \frac{P}{\omega U} \frac{E_0^2 L^2}{P}$$

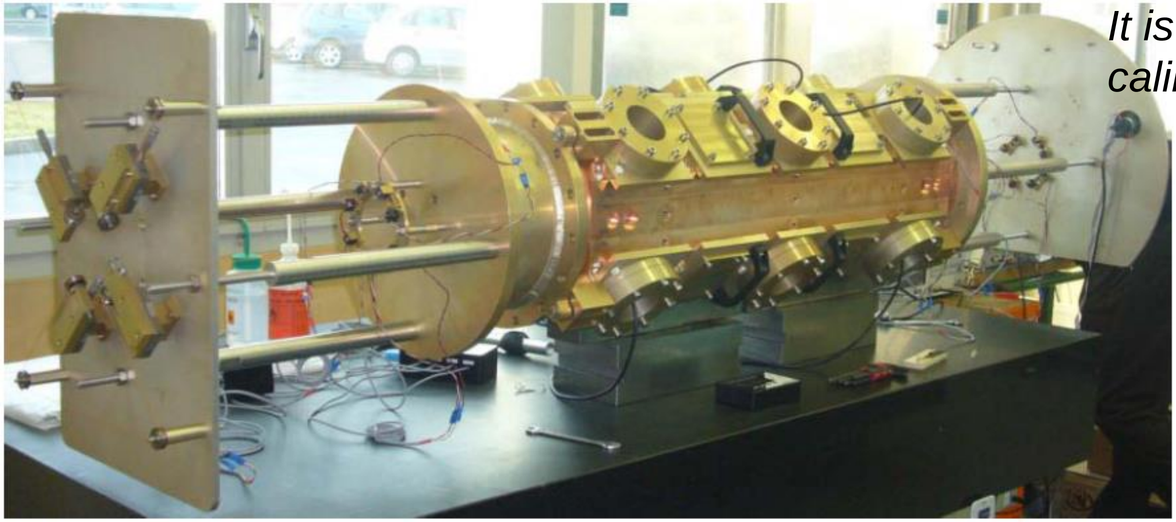
Field measurements

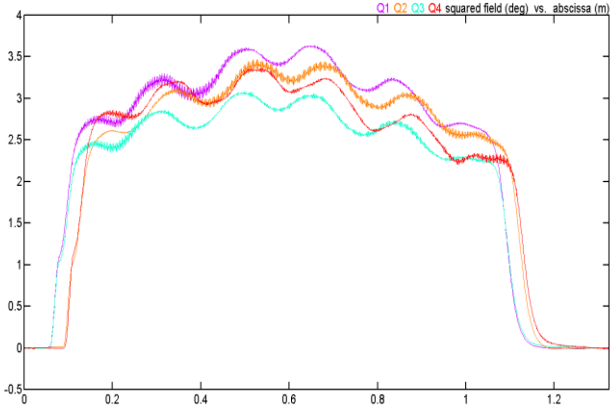


“bead-pull” perturbative measurement.

A small metallic bead is slowly moved inside the resonator.
Slater’s perturbation theorem: the variation in resonant frequency is proportional to the difference between square of electric field and square of magnetic field at the position of the bead.

Bead in regions of pure E or pure B field: easy way to plot the longitudinal field distribution.
It is a relative measurement (or needs calibration of the bead)





Questions on Module 4 ?

- Building blocks of a linear accelerator unit and their interrelations
- Construction: from a sketch to the drawing board to the metal
- From accelerators to circuit theory, how accelerator parameters are defined by electrical parameters