LINACS

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Contents

credits

- much of the material is taken directly from Thomas Wangler USPAS course (http://uspas.fnal.gov/materials/SNS_Front-End.ppt.pdf) and Mario Weiss and Pierre Lapostolle report (**Formulae and procedures useful for the design of linear accelerators, from CERN doc server**)

- from previous linac courses at CAS and JUAS by Erk Jensen, Nicolas Pichoff, Andrea Pisent,Maurizio Vretenar , (http://cas.web.cern.ch/cas)

LECTURE 1

- what is a LINAC
- historical introduction
- parameters of a Radio Frequency (RF) cavity

motivation

- particle beams accelerated in controlled condition are the probe for studying/acting the structure of matter and of the nucleus

- controlled condition means generating a high flux of particles at a precise energy and confined in a small volume in space

what is a linac

- LINear ACcelerator : single pass device that increases the energy of a charged particle by means of an electric field
- Motion equation of a charged particle in an electromagnetic field

$$\frac{d^2\vec{x}}{dt^2} = \frac{q}{m} \cdot \left(\vec{E} + \frac{d\vec{x}}{dt} \times \vec{B} \right)$$

$\vec{x}$ = position vector

q, m = charge, mass

$\vec{E}, \vec{B}$ = electric, magnetic field

t = time

what is a linac-cont’ed

$$\frac{d^2\vec{x}}{dt^2} = \frac{q}{m} \cdot \left(\vec{E} + \frac{d\vec{x}}{dt} \times \vec{B} \right)$$

type of particle :
charge couples with the field, mass slows the acceleration

type of structure

Rate of change of energy

$$\frac{d^2\vec{x}}{dt^2} = \frac{q}{m}\cdot\left(\vec{E} + \frac{d\vec{x}}{dt}\times\vec{B}\right)$$

can be written as :

$$\frac{d\vec{p}}{dt} = q\cdot\left(\vec{E} + \frac{d\vec{x}}{dt}\times\vec{B}\right)$$

$\vec{p} = momentum$

$W = energy$

$$\frac{dW}{dt} = \frac{d\vec{x}}{dt}\bullet\frac{d\vec{p}}{dt} = q\cdot\frac{d\vec{x}}{dt}\bullet\left(\vec{E} + \cancel{\frac{d\vec{x}}{dt}\times\vec{B}}\right)$$

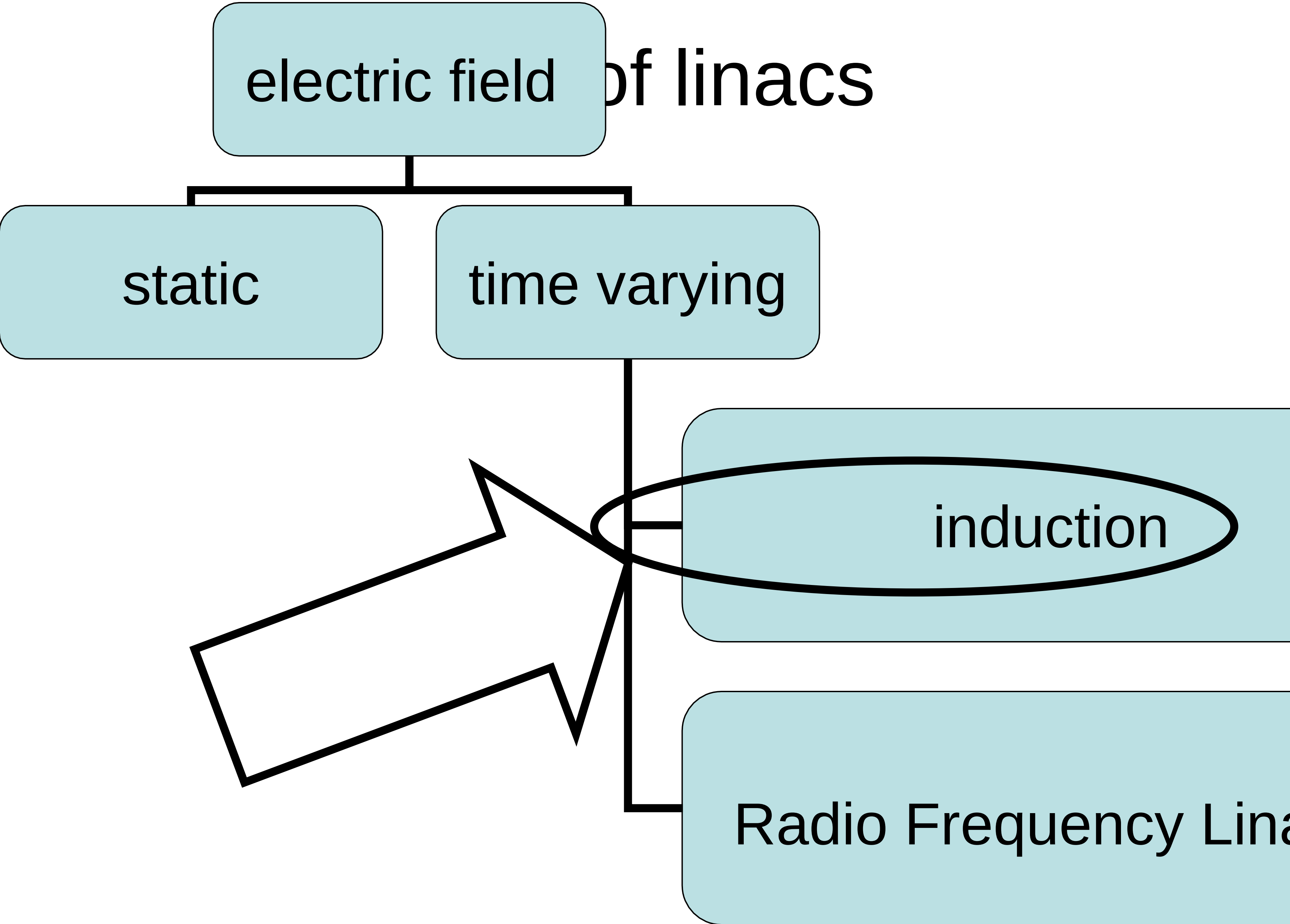
Energy change via the electric field

type of particles – 4 groups

- Electrons :
  - High energy collider
  - High-quality e- beam for FEL;
  - Medical/Industrial irradiation;
  - Neutron sources
- protons and light ions :
  - Synchrotron injectors : High intensity, high duty-cycle
  - Neutron sources : High Power. Material study, transmutation, nuclear fuel production, irradiation tools, exotic nucleus production
  - Medical applications : Medium-low intensity and energy, very controlled parameters
- heavy ions
  - Nuclear physics research : High intensity, high duty-cycle
  - Implantation : Semi-conductors
  - Driver for inertial-confinement fusion

- short lived particles (e.g. muons)

# of linacs



electric field

static

time varying

induction

Radio Frequency Lina

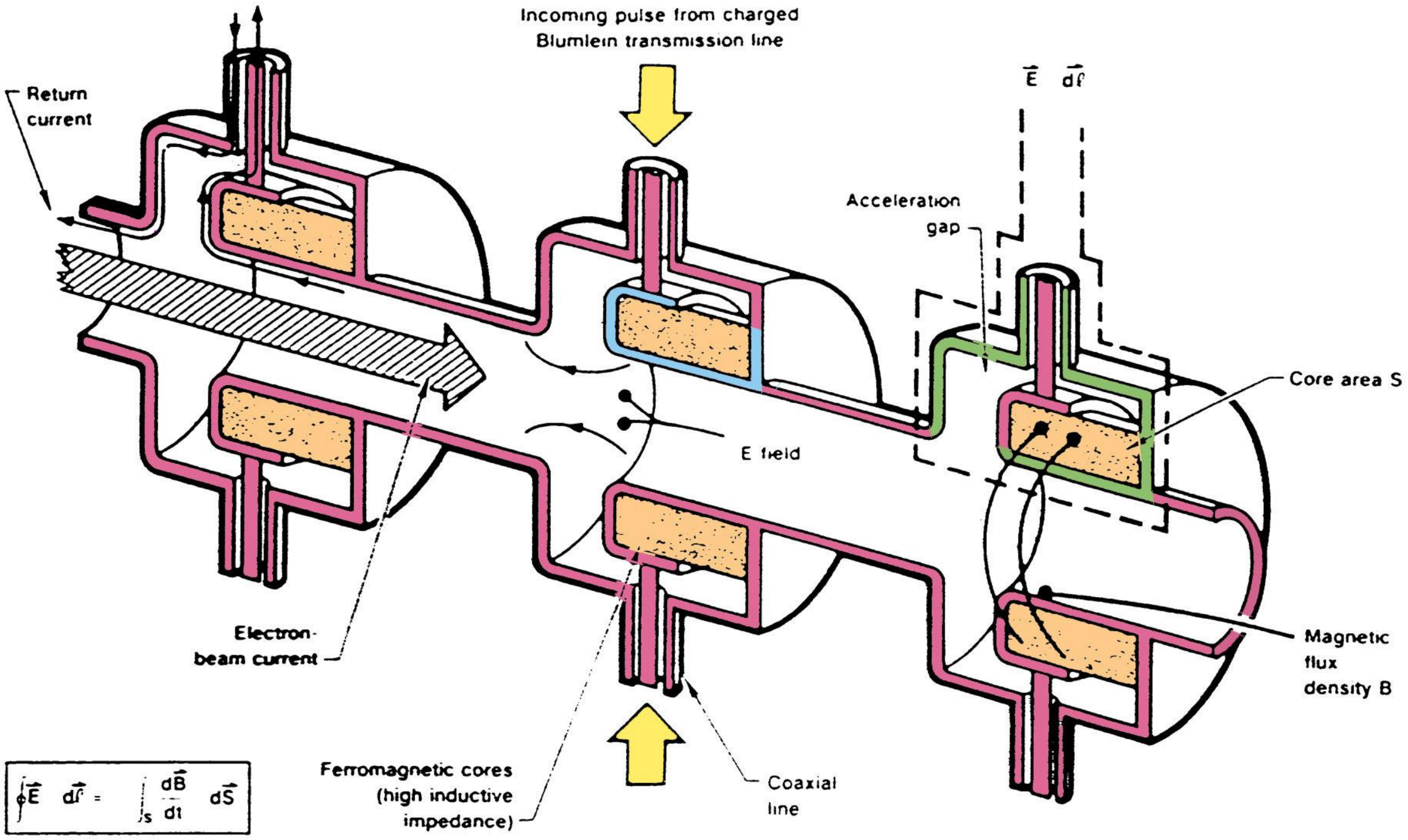
static linac

- device which provides a constant potential difference (and consequently electric field). Definition of the Volt, measure of the energy in eV.

- acceleration is limited to few MeV. Limitation comes from electric field breakdown

- still used in the very first stage of acceleration when ions are extracted from a source.

induction linac

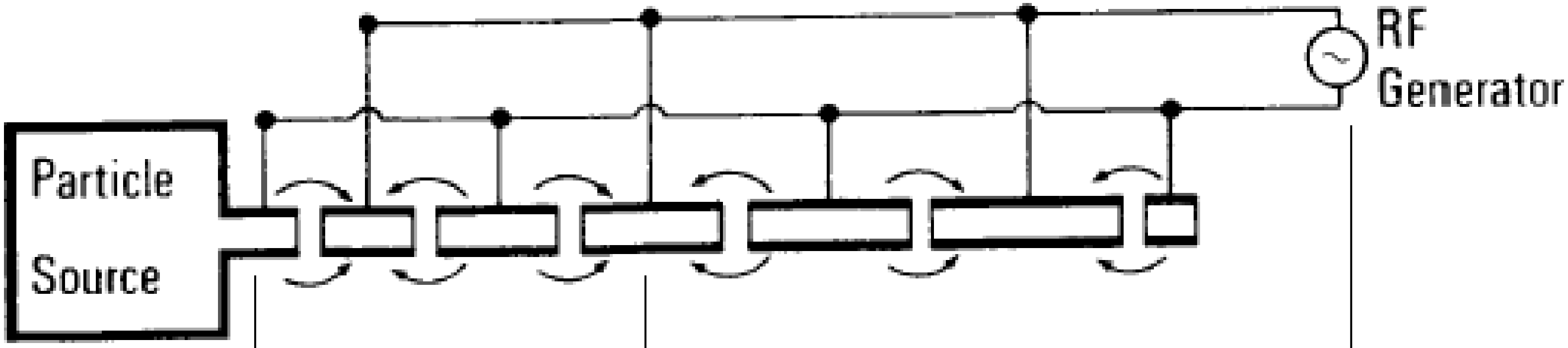


The magnetic induction accelerator principle

Radio Frequency Linac

- acceleration by time varying electromagnetic field overcomes the limitation of static acceleration
- First experiment towards an RF linac : Wideroe linac 1928
- First realization of a linac : 1931 by Sloan and Lawrence at Berkeley laboratory

Wideroe linac 1928



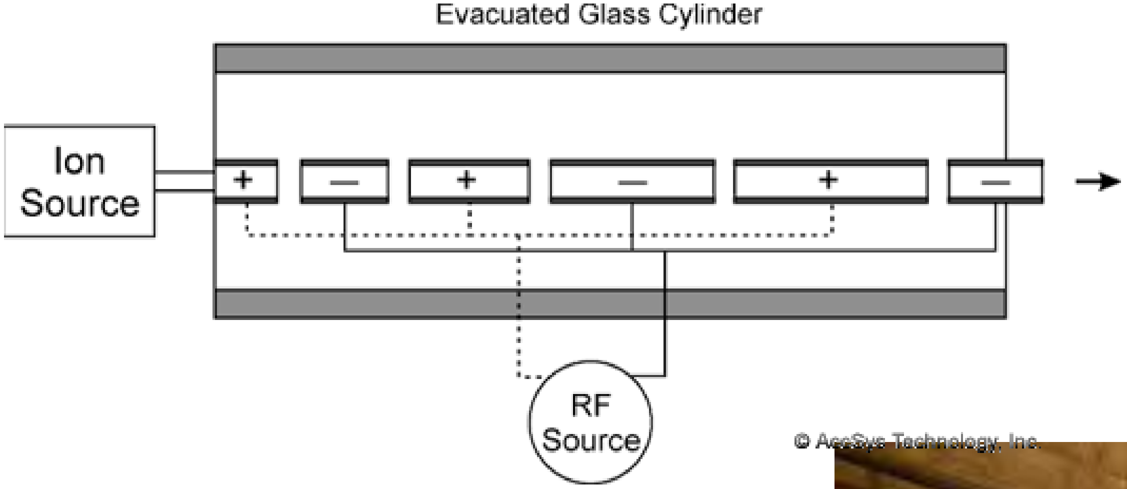
potassium ion-
BUNCHED

lenght of the tube
proportional to the
velocity

25 kV 1 MHz

- the energy gained by the beam (50 keV) is twice the applied voltage (25 keV at 1 MHz)

From Wideroe to Alvarez



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from Wideroe to Alvarez linac

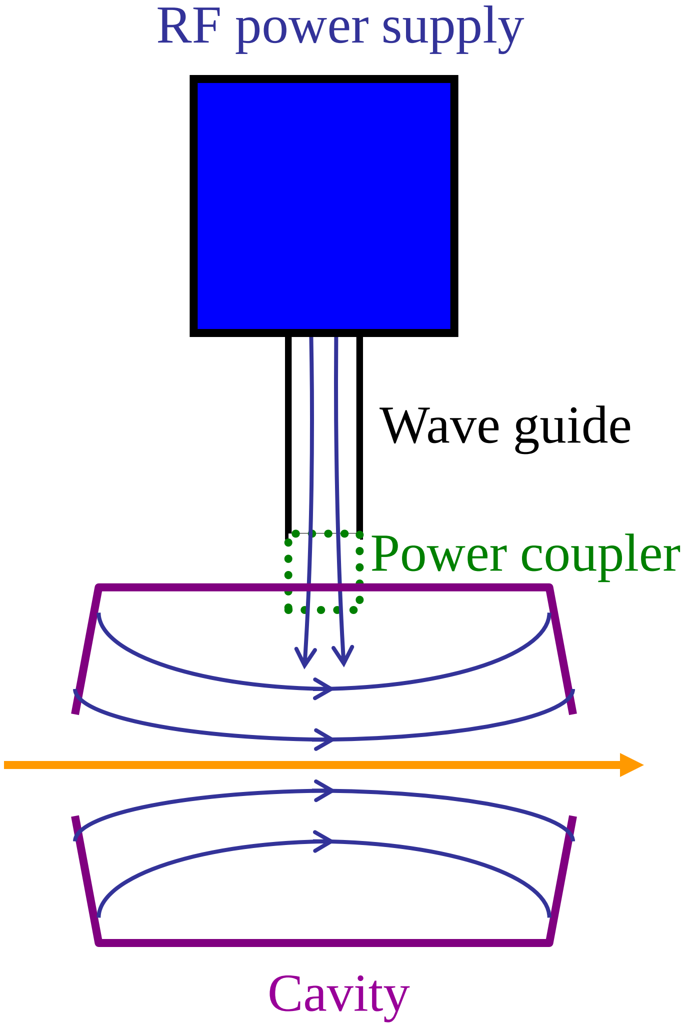
- to proceed to higher energies it was necessary to increase by order of magnitude the frequency and to enclose the drift tubes in a cavity (resonator)

- this concept was proposed and realized by Luis Alvarez at University of California in 1955 : A 200 MHz 12 m long Drift Tube Linac accelerated protons from 4 to 32 MeV.

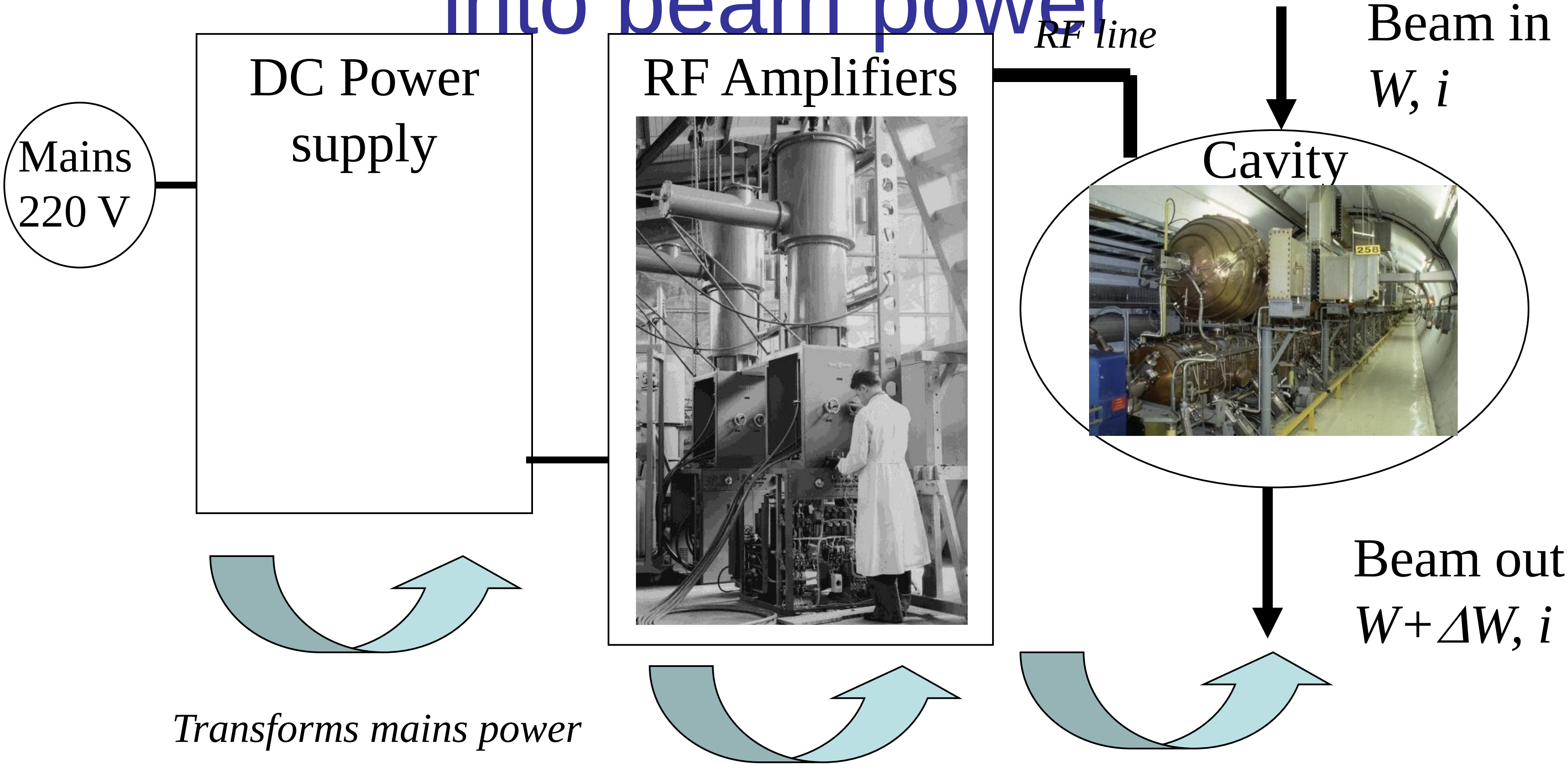
- the realization of the first linac was made possible by the availability of high-frequency power generators developed for radar application during World War II

principle of an RF linac

1) RF power source: generator of electromagnetic wave of a specified frequency. It feeds a
2) Cavity : space enclosed in a metallic boundary which resonates with the frequency of the wave and tailors the field pattern to the
3) Beam : flux of particles that we push through the cavity when the field is maximized as to increase its
4) Energy.



A (Linac) RF System:
transforms mains power into beam power



Mains 220 V

DC Power supply

RF Amplifiers

RF line

Beam in W, i

Cavity

Beam out $W+\Delta W, i$

Transforms mains power into DC power

Transforms DC power into RF power [klystron/tube efficiency]

Transforms RF power into beam energy [efficiency=shunt impedance]

designing an RF LINAC

- cavity design : 1) control the field pattern inside the cavity; 2) minimise the ohmic losses on the walls/maximise the stored energy.

- beam dynamics design : 1) control the timing between the field and the particle, 2) insure that the beam is kept in the smallest possible volume during acceleration

electric field in a cavity

- assume that the solution of the wave equation in a bounded medium can be written as

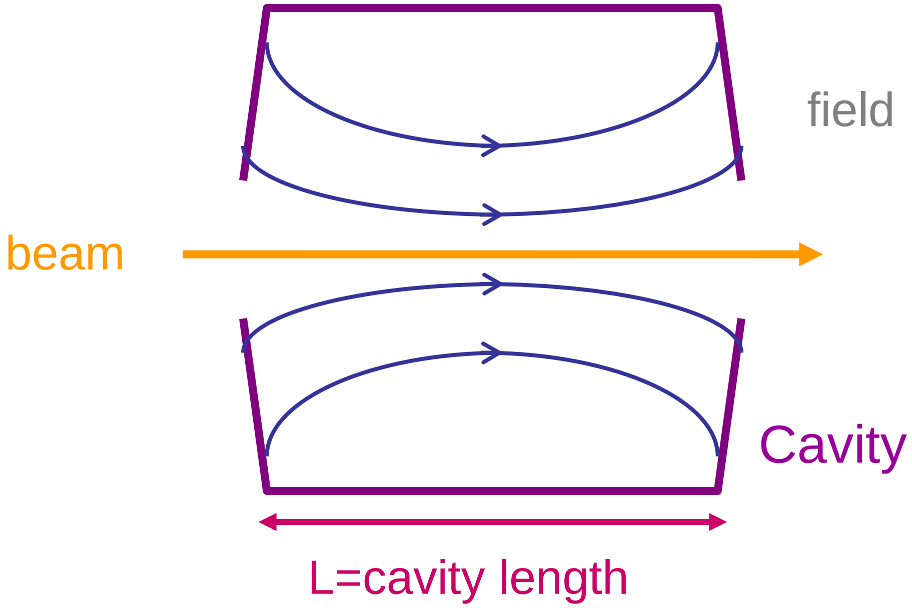
$$\mathrm{E}(x,y,z,t) = E(x,y,z)\cdot e^{-j\omega t}$$

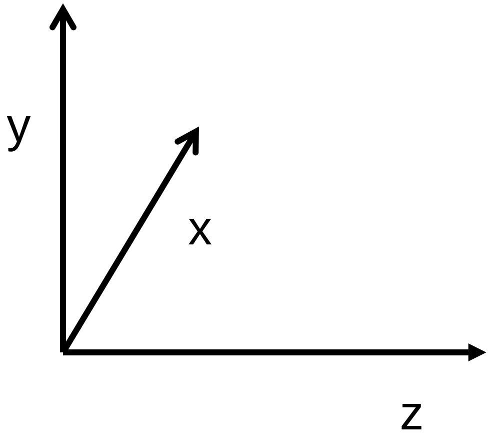
function of space

function of time oscillatin
at freq = ω/2π

- cavity design step 1 : concentrating the RF power from the generator in the area traversed by the beam in the most efficient way. i.e. tailor E(x,y,z) to our needs by choosing the appropriate cavity geometry.

cavity geometry and related parameters definition





1-Average electric field

2-Shunt impedance

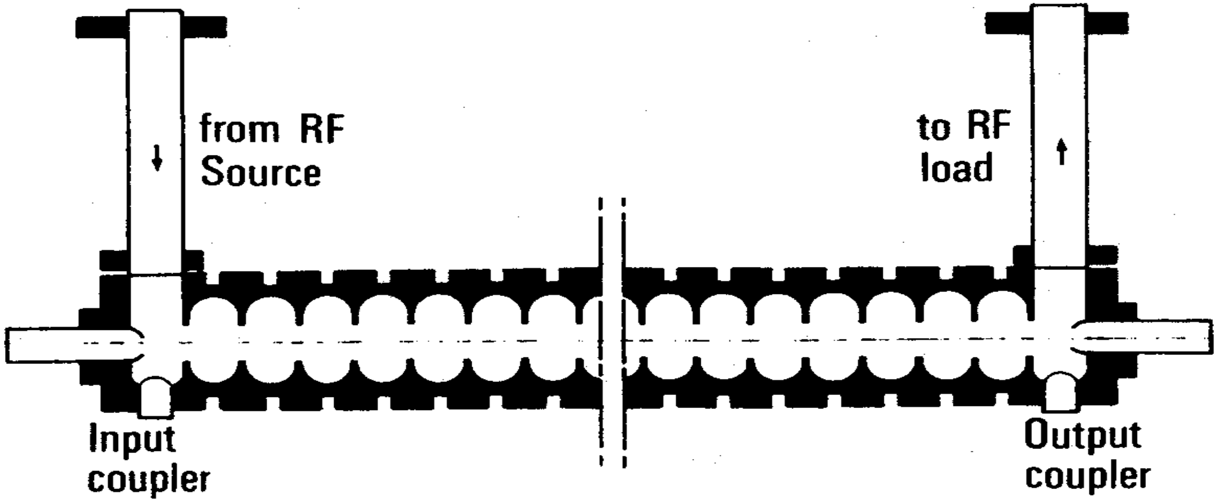
3-Quality factor

4-Filling time

5-Transit time factor

6-Effective shunt impedance

standing vs. traveling wave



Standing Wave cavity : cavity where the forward and backward traveling wave have positive interference at any point

cavity parameters-1

- Average electric field (E_0 measured in V/m) is the space average of the electric field along the direction of propagation of the beam in a given moment in time when F(t) is maximum. $\mathrm{E}(x,y,z,t) = E(x,y,z)\cdot e^{-j\omega t}$

$$E_0 = \frac{1}{L}\int_0^L E_z(x=0, y=0, z)dz$$

- physically it gives a measure how much field is available for acceleration
- it depends on the cavity shape, on the resonating mode and on the frequency

cavity parameters-2

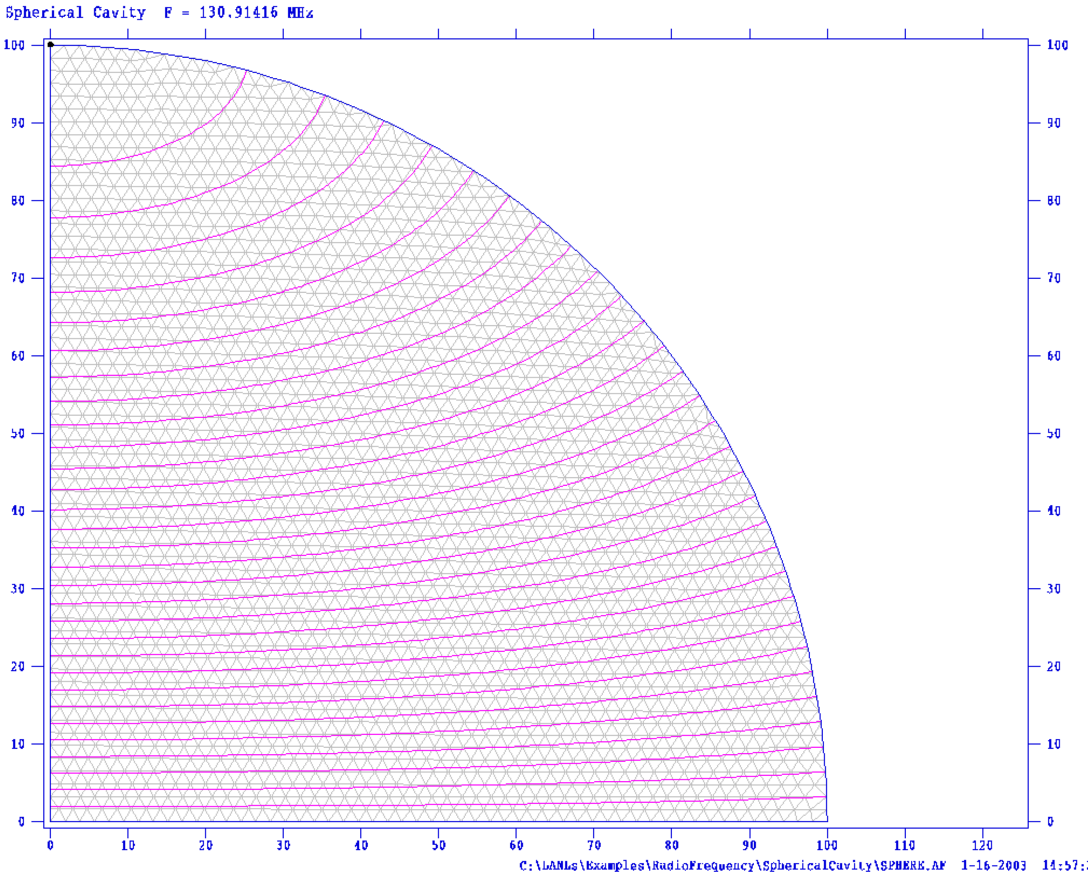
- Shunt impedance (Z measured in Ω/m) is defined as the ratio of the average electric field squared (E0) to the power (P) per unit length (L) dissipated on the wall surface.

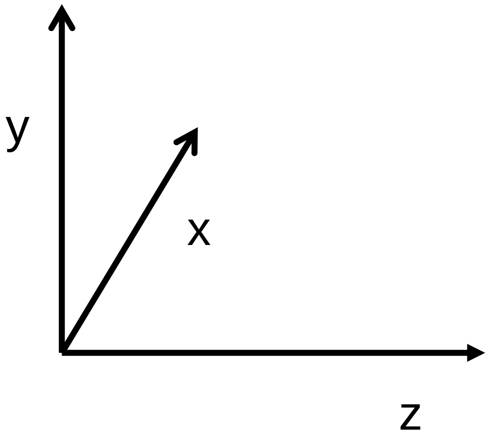
$$Z = \frac{E_0^2}{} \cdot \frac{L}{P} \quad \text{or} \quad Z = \frac{E_0^2}{} \cdot \frac{dL}{dP} \quad \text{for TW}$$

- Physically it is a measure of well we concentrate the RF power in the useful region .
- NOTICE that it is independent of the field level and cavity length, it depends on the cavity mode and geometry.
- beware definition of shunt impedance !!! some people use a factor 2 at the denominator ; some (other) people use a definition dependent on the cavity length.

cavity parameters-2

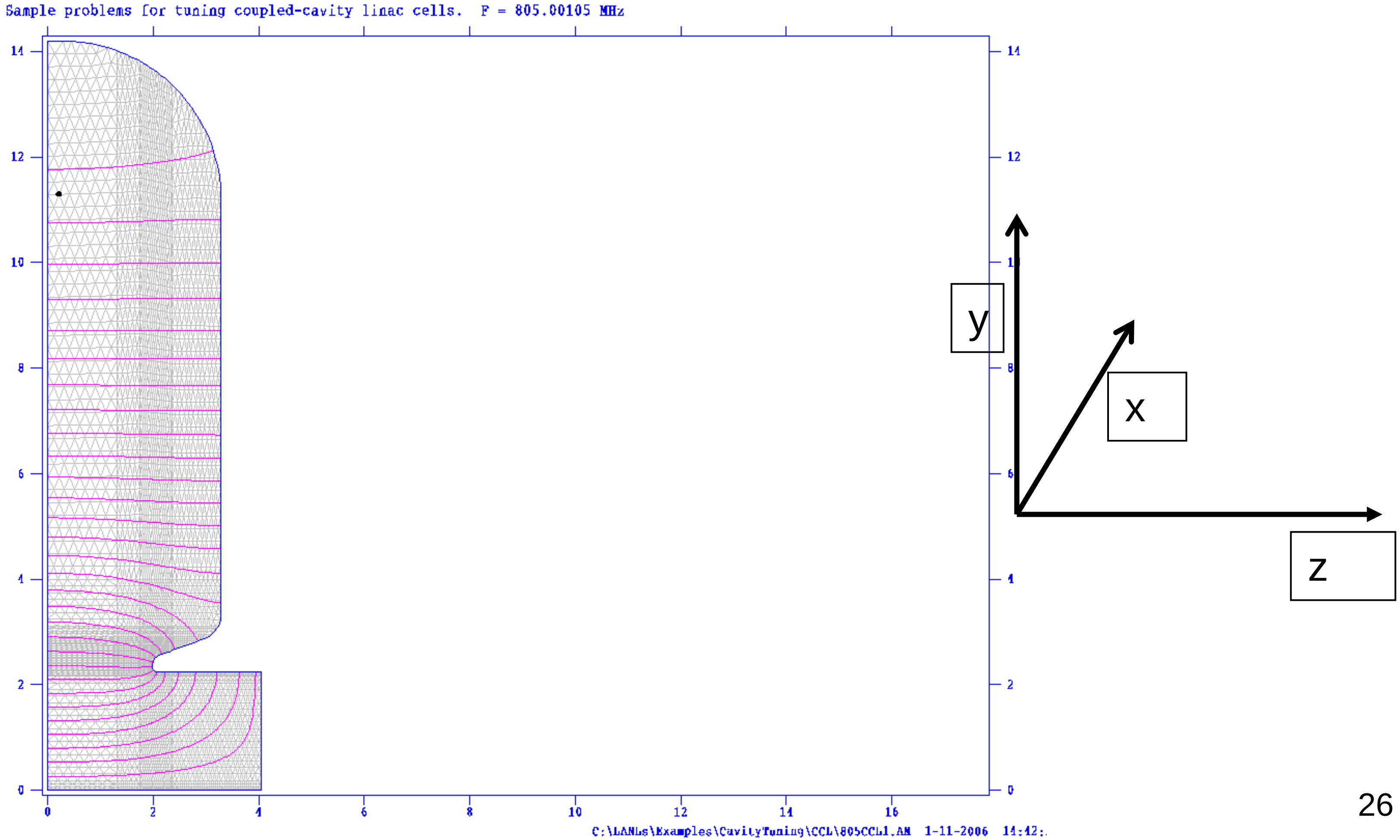
optimized (from the ZTT point of view) cavity offers minimum surface for the max volume : spherical cavity.





cavity parameters-2

But a more realistic shape includes –at least- an iris for the beam to pass through!



cavity parameters-3

- Quality factor (Q dimension-less) is defined as the ratio between the stored energy (U) and the power lost on the wall (P) in one RF cycle (f=frequency)

$$Q = \frac{2 \cdot \pi \cdot f}{P} \cdot U$$

- Q is a function of the geometry and of the surface resistance of the material :

superconducting (niobium) : Q= 10^{10}
normal conducting (copper) : Q=10^{4}

example at 700MHz

cavity parameters-3

- SUPERCONDUCTING Q depends on temperature :
  - $8*10^9$ for 350 MHz at 4.5K
  - $2*10^{10}$ for 700 MHz at 2K.
- NORMAL CONDUCTING Q depends on the mode :
  - 10^4 for a TM mode (Linac2=40000)
  - 10^3 for a TE mode (RFQ2=8000).

cavity parameters-4

- filling time (τ measured in sec) has different definition on the case of traveling or standing wave.

- TW : the time needed for the electromagnetic energy to fill the cavity of length *L*

$$t_F = \int_0^L \frac{dz}{v_g(z)}$$

velocity at which the energy propagates through the cavity

- SW : the time it takes for the field to decrease by 1/e after the cavity has been filled

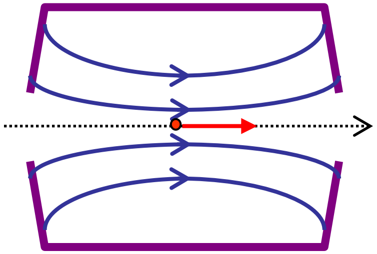
$$t_F = \frac{2Q}{\omega}$$

measure of how fast the stored energy is dissipated on the wall

cavity parameters-5

- transit time factor (T, dimensionless) is defined as the maximum energy gain per charge of a particles traversing a cavity over the average voltage of the cavity.
- Write the field as

$$Ez(x,y,z,t) = E_z(x,y,z)e^{-i(\omega t)}$$



- The energy gain of a particle entering the cavity on axis at phase φ is
- $$\Delta W = \int_0^L qE_z(o,o,z)e^{-i(\omega t+\phi)}dz$$

cavity parameters-5

- assume constant velocity through the cavity (APPROXIMATION!!) we can relate position and time via

$$z = v \cdot t = \beta c t$$

- we can write the energy gain as

$$\Delta W = qE_0 LT \cos(\phi)$$

- and define transit time factor as

$$T = \frac{\left| \int_0^L E_z(z) e^{-j\left(\frac{\omega z}{\beta c}\right)} dz \right|}{\int_0^L E_z(z) dz}$$

T depends on the particle velocity and on the gap length. IT DOESN"T depend on the field

cavity parameters-5

- NB : Transit time factor depends on x,y (the distance from the axis in cylindrical symmetry). By default it is meant the transit ime factor on axis
- Exercise!!! If $E_z = E_0$ then

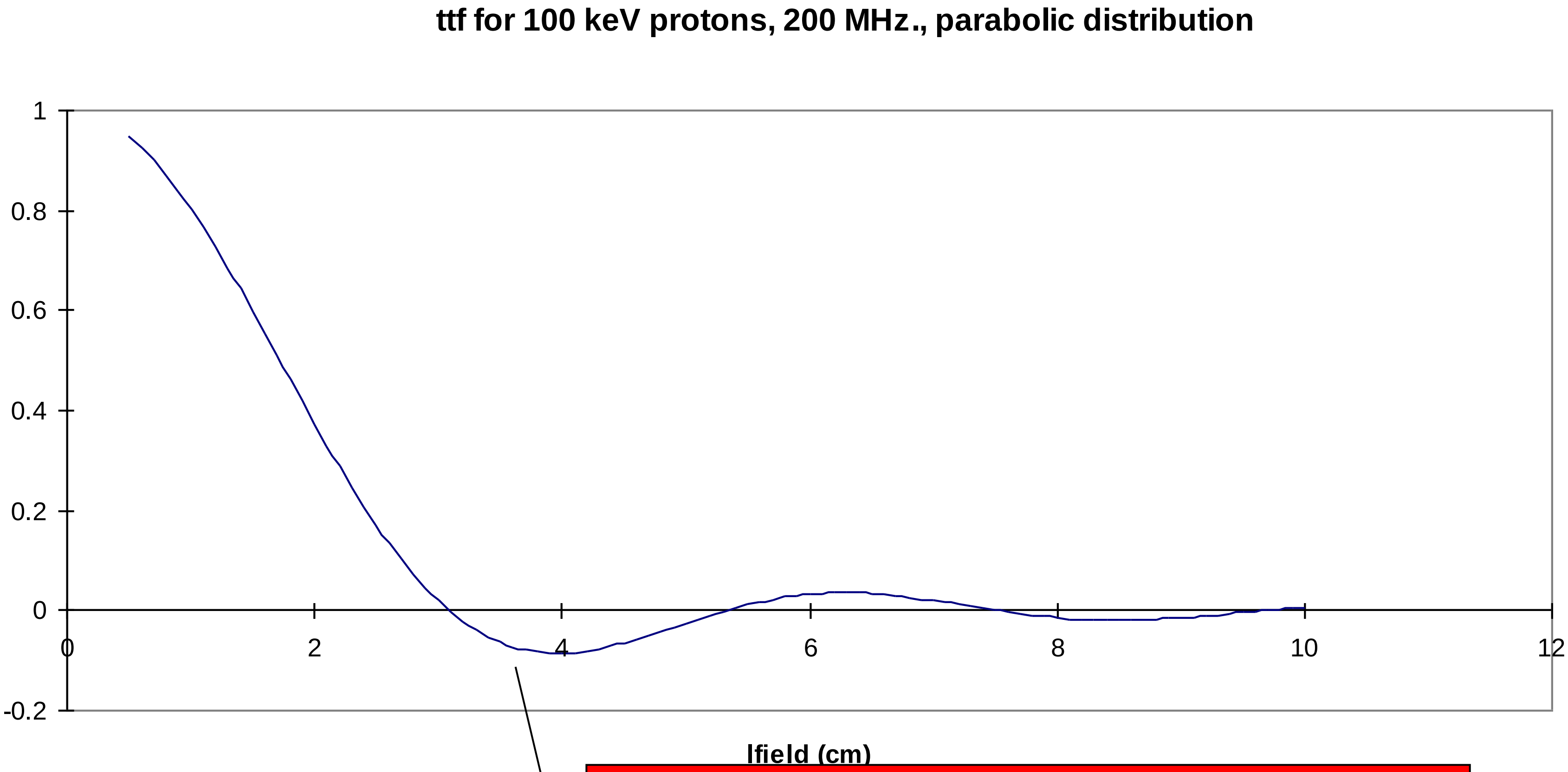
L=gap lenght

β=relativistic parametre

λ=RF wavelenght

$$T = \frac{\sin\left(\frac{\pi L}{\beta\lambda}\right)}{\left(\frac{\pi L}{\beta\lambda}\right)}$$

cavity parameter-6



if we don’t get the length right we can end up decelerating!!!

effective shunt impedance

- It is more practical, for accelerator designers to define cavity parameters taking into account the effect on the beam

- Effective shunt impedance ZTT

$$Z = \frac{E_0^2}{\,} \cdot \frac{L}{P}$$

$$ZTT = \frac{(E_0 T)^2}{\,} \cdot \frac{L}{P}$$

measure if the structure design is optimized

measure if the structure is optimized and adapted to the velocity of the particle to be accelerated

limit to the field in a cavity

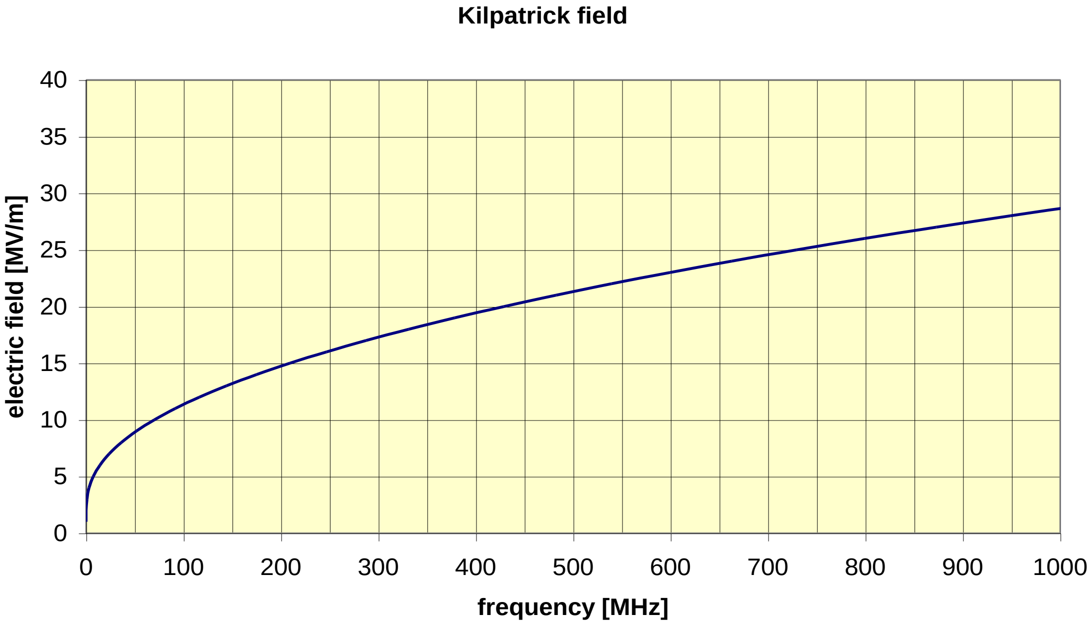
- normal conducting :
  - heating
  - Electric peak field on the cavity surface (sparking)

- super conducting :
  - quenching
  - Magnetic peak field on the surface (in Niobium max 200mT)

Kilpatrick sparking criterion

(in the frequency dependent formula)

$$f = 1.64\, E^{2} \exp(-8.5/E)$$



GUIDELINE nowadays : peak surface field up to 2*kilpatrick field

Quality factor for normal conducting cavity is $E_{peak}/E_{o}T$

summary of lesson 1

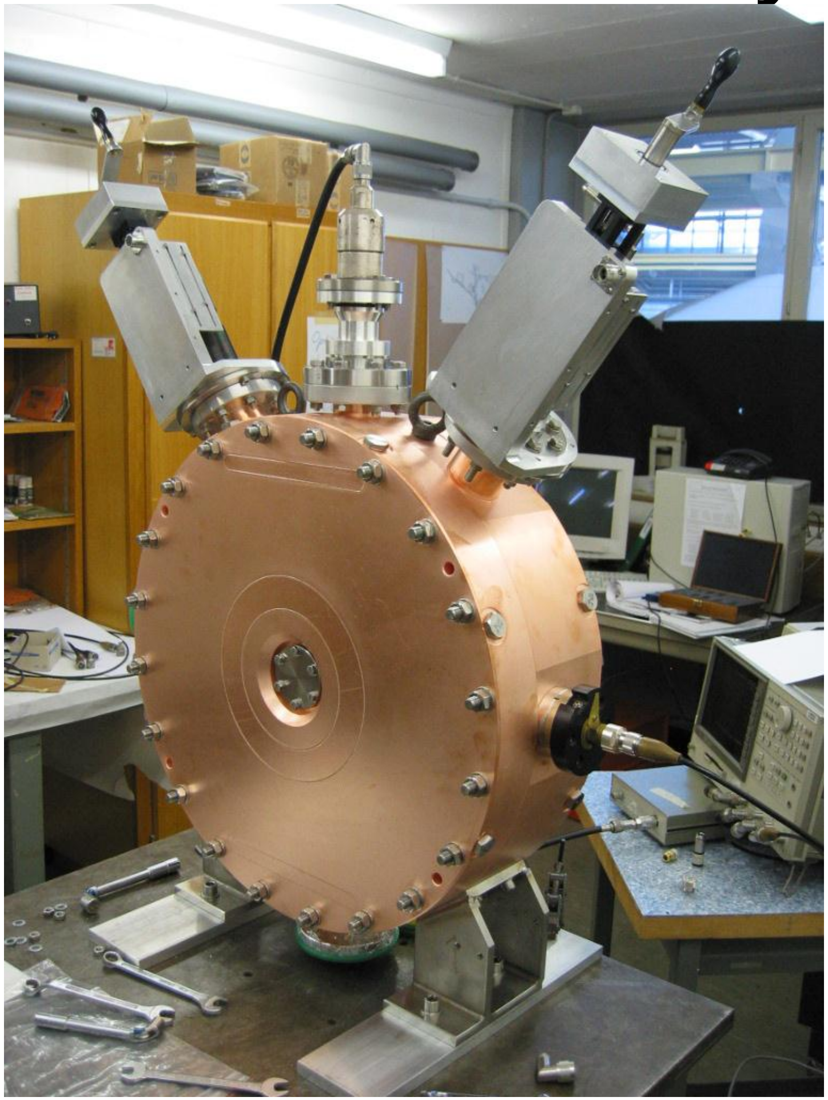
- first step to accelerating is to fill a cavity with electromagnetic energy to build a resonant field.

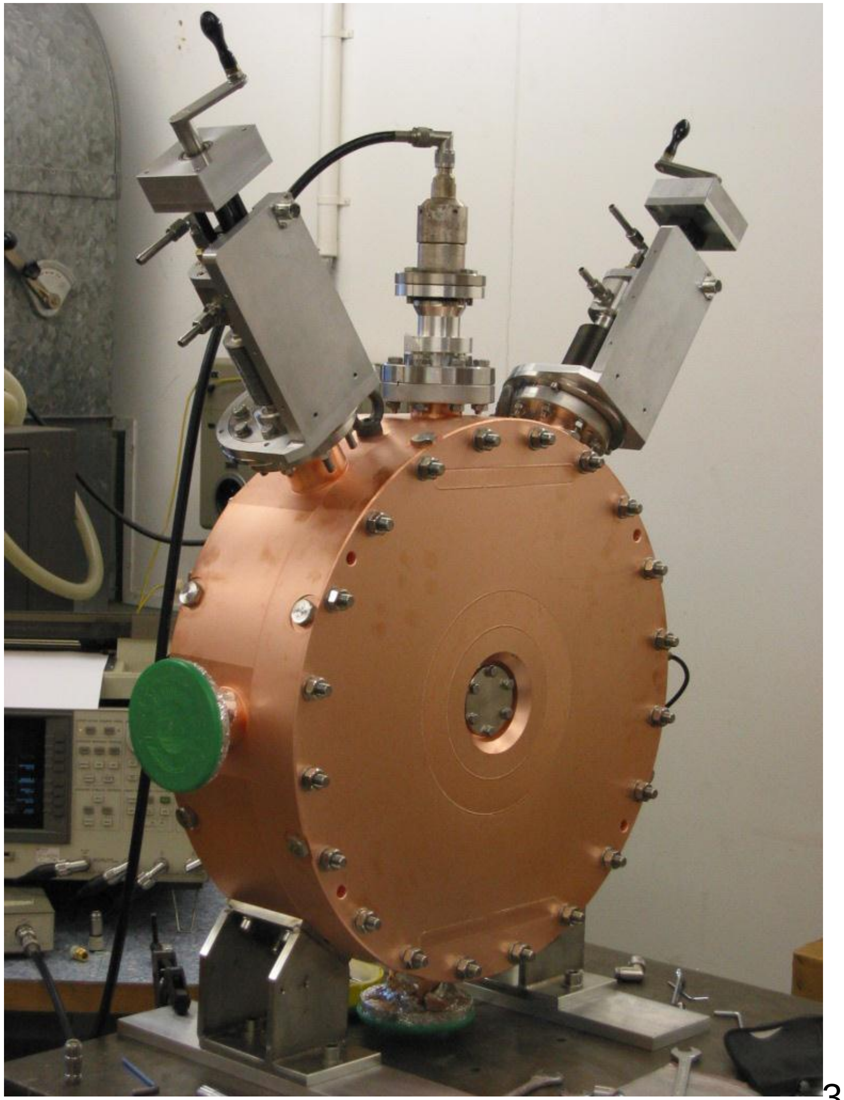
in order to be most efficient one should :

1) concentrate the field in the beam area
2) minimise the losses of RF power
3) control the limiting factors to putting energy into the cavity

- This is achieved by shaping the cavity in the appropriate way

352 MHz cavity for 3 MeV protons





88 MHz cavity for muons

88 MHz cavity

2 MW amplifier

Nose Cone (closed gap)