JUAS 2017

LINACS

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http://jlalleme.web.cern.ch/jlalleme/Juas2017/

Credits

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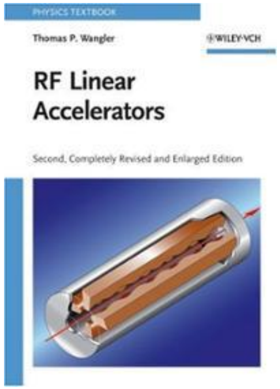
Much material is taken from:

- Thomas Wangler, RF linear accelerators



- Nicolas Pichoff – from previous CAS school
- Maurizio Vretenar – from previous CAS school

  http://cas.web.cern.ch/cas/

- Alessandra Lombardi – from previous JUAS school

Before starting

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- Please, ask questions…..
  - During the lecture.
  - During the tutorial.
  - Feel free to contact me later.

- We will put together many concepts already seen : Relativity, Electromagnetism, RF, Transverse and Longitudinal beam dynamics…

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Organization of the Lecture

- 3 hours + 3 hours tutorial

WEEK 2

Schedule 2017	Monday Jan 16th	Tuesday Jan 17th	Wednesday Jan 18th	Thursday Jan 19th	Friday Jan 20th
09:00	*Bus leaves at 07:30 from JUAS* *(2 hours of travel by bus)*	Longitudinal Dynamics lecture *E. Métral*	Linacs lecture *J-B. Lallement*	Longitudinal Dynamics lecture *E. Métral*	Cyclotrons lecture *B. Jacquot*
10:00		Coffee Break	Coffee Break	Coffee Break	Coffee Break
10:15	VISIT AT ESRF	Longitudinal Dynamics tutorial *E. Métral/B. Salvant*	Longitudinal Dynamics lecture *E. Métral*	Longitudinal Dynamics lecture *E. Métral*	Cyclotrons lecture *B. Jacquot*
11:15		Longitudinal Dynamics lecture *E. Métral*	Longitudinal Dynamics tutorial *E. Métral/B. Salvant*	Longitudinal Dynamics lecture *E. Métral*	Cyclotrons tutorial *B. Jacquot*
12:15	*(Lunch offered by ESRF)*	BREAK	BREAK	BREAK	BREAK
14:00	14:00 - 16:00 Injection / Extraction lecture *Thomas Perron*	Linacs lecture *J-B. Lallement*	Longitudinal Dynamics lecture *E. Métral*	Cyclotrons lecture *B. Jacquot*	Longitudinal Dynamics lecture *E. Métral*
15:00		Linacs lecture *J-B. Lallement*	Linacs tutorial *J-B. Lallement /V. Dimov*	Cyclotrons tutorial *B. Jacquot*	Longitudinal Dynamics tutorial *E. Métral/B. Salvant*
16:00		Coffee Break	Coffee Break	Coffee Break	Coffee Break
16:15	*Bus leaves at 17:00 from ESRF*	Linacs tutorial *J-B. Lallement /V. Dimov*	Linacs tutorial *J-B. Lallement /V. Dimov*	Cyclotrons lecture *B. Jacquot*	Longitudinal Dynamics tutorial *E. Métral/B. Salvant*
17:15		LHC & Future High-Energy Circular Collider Seminar *F. Bordry*			
18:15					

Organization of the Lecture

- 3 hours + 3 hours tutorial
- Lecture

  Part1: Introduction to Linacs.

  Part2: Cavities and structures.

  Part3: Beam dynamics.

  Part4: Bonus

- Tutorial

  Several problems to better understand and put in practice the different concepts.

Part1: Introduction

- What is a LINAC
- A bit of history
- Why a LINAC
- Principle of RF LINACs

What is a LINAC

- **LINear ACcelerator :** A device where charged particles acquire energy moving on a linear path.

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

Acceleration related to the sum of the forces

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

Momentum

$$\frac{dW}{dt} = \frac{d\vec{z}}{dt}.\frac{d\vec{p}}{dt} = q.\frac{d\vec{z}}{dt}.\left(\vec{E} + \frac{d\vec{z}}{dt} \times \vec{B}\right)$$

Energy gain !

Energy gain thanks to the electric field.

What is a LINAC

- **LINear ACcelerator :** A device where charged particles acquire energy moving on a linear path.

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

Type of the accelerated Particles

- Charge
- Mass

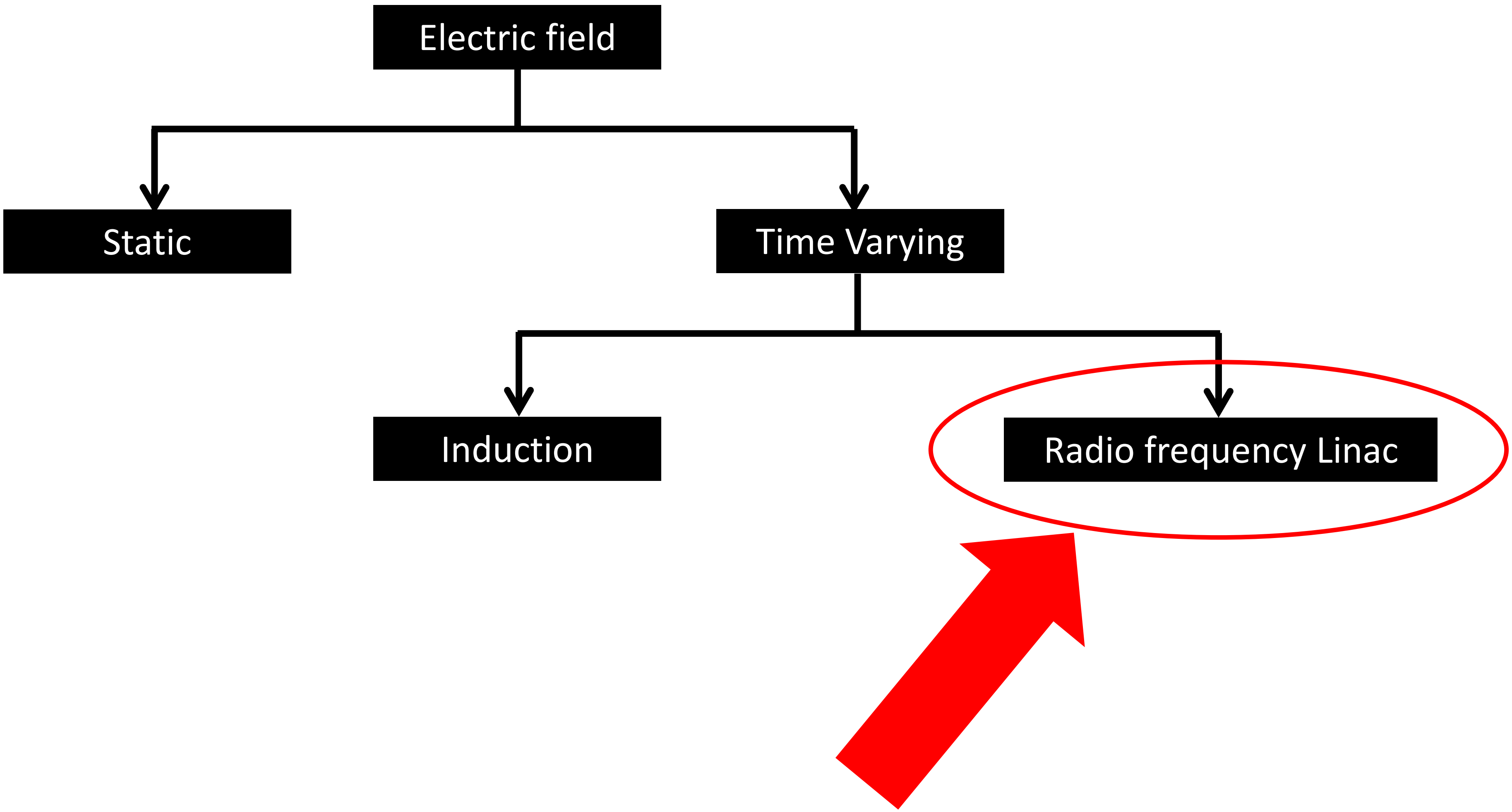
Mainly:

Electrons
Protons and light ions
Heavy ions

Type of the accelerating sturcture

- Electric field for acceleration
- Magnetic field for focusing/bending

Different type of LINACs



What we will discuss during 6 hours !!!

Example of a static Linac

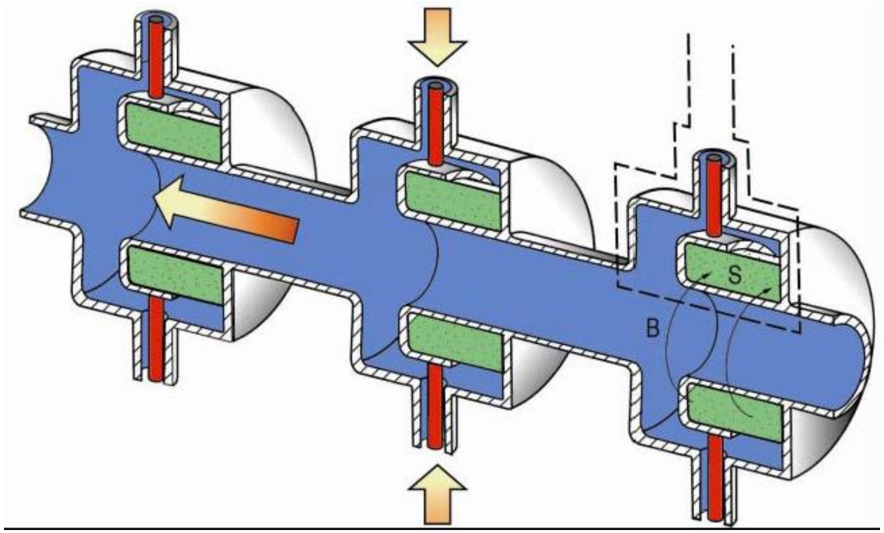
Constant potential difference (electric field)
Energy gain in [eV]

Acceleration limited to few MeV (electric field breakdown)

Still used in very first stage of acceleration

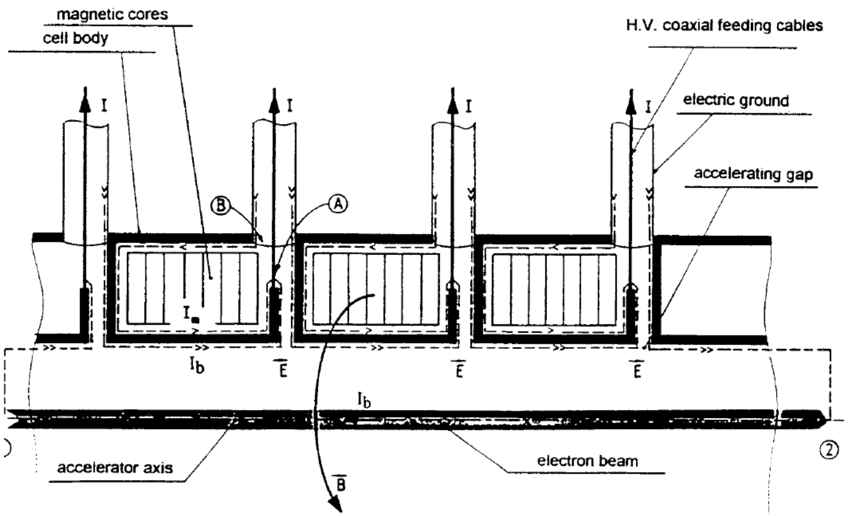
Picture : 750 kV Cockcroft-Walton Linac2 injector at CERN from 1978 to 1992.

Principle of the induction linac



A varying magnetic field can generate an electric field.

$$V_0 = \oint \vec{E}.d\vec{l} = \iint_s \frac{d\vec{B}}{dt}.d\vec{S}$$



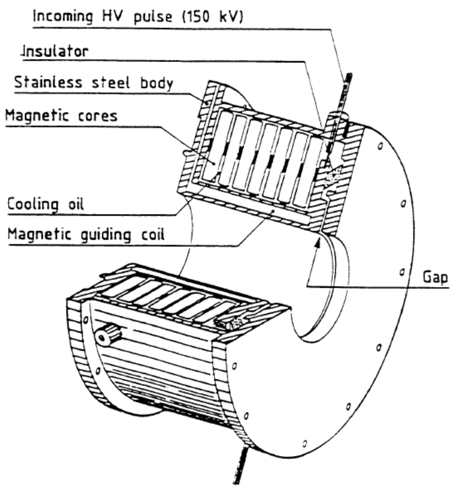


Fig. 2 Induction cell

The first Radio Frequency Linac

Acceleration by time varying electromagnetic field overcome the limitation of static fields.

First RF linac design and experiment – Wideroe Linac in 1928

K beam – 2*25 kV = 50 keV

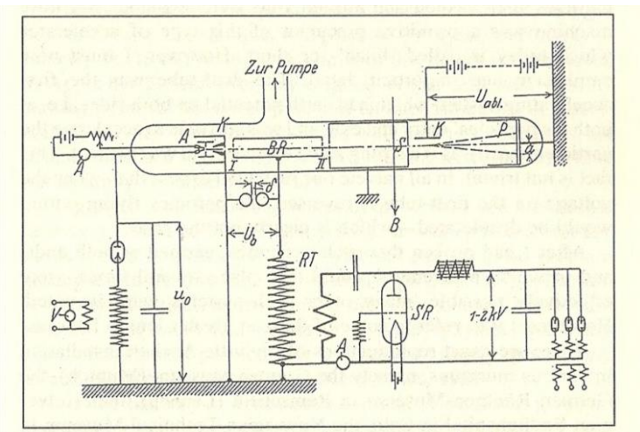
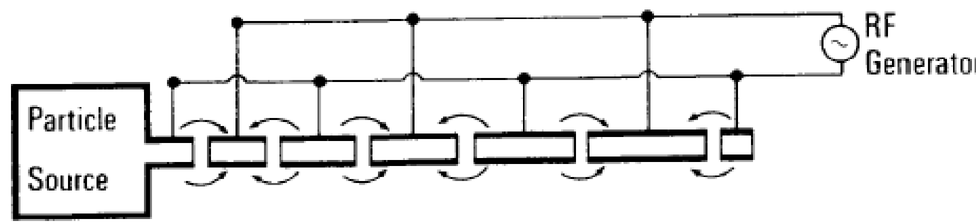
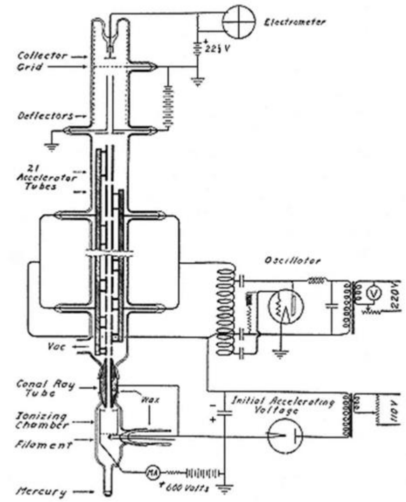


Fig. 3.6: Acceleration tube and switching circuits [Wi28].



First working Linac – Berkeley in 1931

Hg beam – 30*42 kV = 1.26 MeV



Big Jump in RF technology – 40's

- Development of Radar technology during the WW II.
- Competences and components in the MHz-GHz range.

From Wideroe to Alvarez

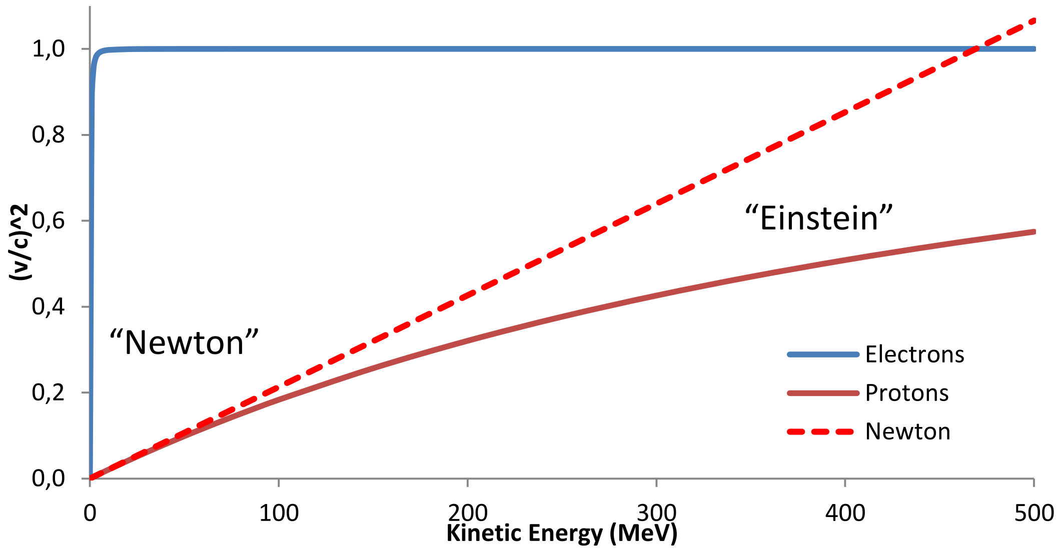
- Drift tubes inside a cavity resonator
- After WW II, 2.000 transmitters at 202.56 MHz from US army stocks
- First Drift Tube Linac in 1955 from 4 to 32 MeV.

Bases of modern RF linac technology !!!

Why LINACs

	LINACS		SYNCHROTRON
Particle	Low Energy	High Energy	High Energy
Protons, Ions	Injector to synchrotrons, stand alone applications. Synchronicity with the RF fields in the range where velocity increase with energy.	Production of secondary beams (n, v, RIB, …) Higher cost/ MeV than synchrotrons High average beam current (repetition rate, less resonnaces, easier beam loss)	Very efficient when velocity is constant (multiple crossing of RF gaps). Limited current (repetition frequency, instabilities)
Electrons	Conventional e- linac Simple and compact	Linear colliders No energy loss due to synchrotron radiation – smaller beam size. Only option for high energy.	Ligth sources Can accumulate high beam intensities.

Why LINACs



Electons mass 511 keV

Proton mass 938.27 MeV (1836 time e- mass)

At 3 MeV, $\beta_{e-} = 0.99$, $\beta_{p+} = 0.08$

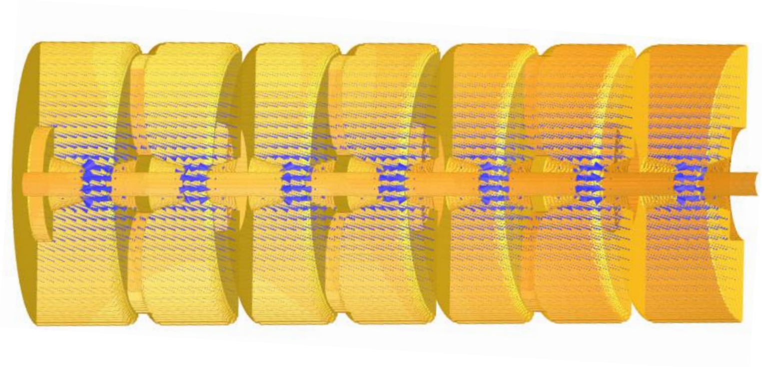
At 500 MeV, $\beta_{p+} = 0.76$

A Linac is a perfect structure to adapt to non-relativistic particles

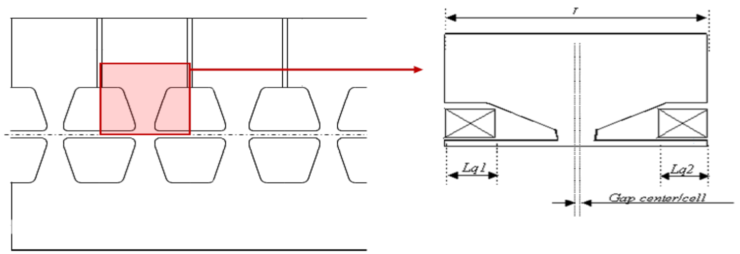
RF acceleration

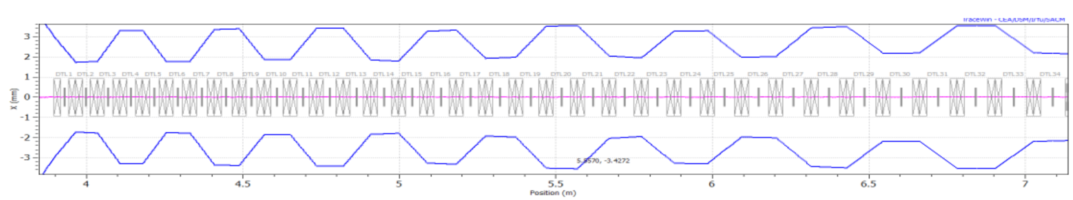
Designing an RF LINAC

1. Cavity design
   - Control the field pattern inside the cavity
   - Minimize the Ohmic losses on the walls/maximize the stored energy



2. Beam dynamics design
   - Control the timing btw field and particles
   - Insure that the beam is kept in the smallest possible volume during acceleration





Electric field in a cavity

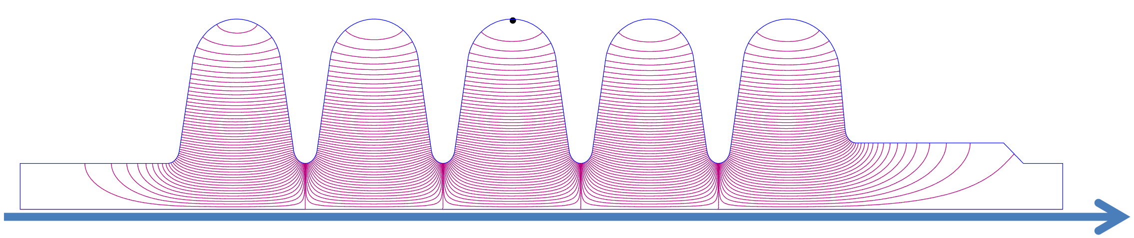
- Assuming that the solution of the wave equation in a bounded medium can be written as

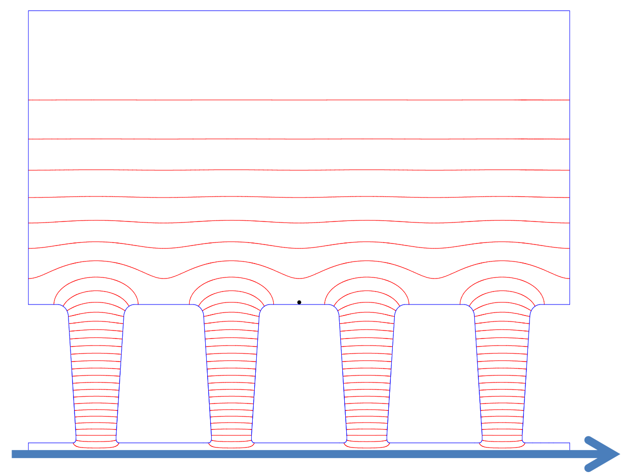
$$E(x,y,z,t) = E(x,y,z).e^{-j\omega t}$$

Function of space → $E(x,y,z)$

Function of time
Oscillating at freq. $\omega/2\pi$ → $e^{-j\omega t}$

- First step in cavity design: Concentrating the RF power on the beam path in the most efficient way. Tailor $E(x,y,z)$ by choosing the appropriate cavity geometry





One word on travelling wave cavities

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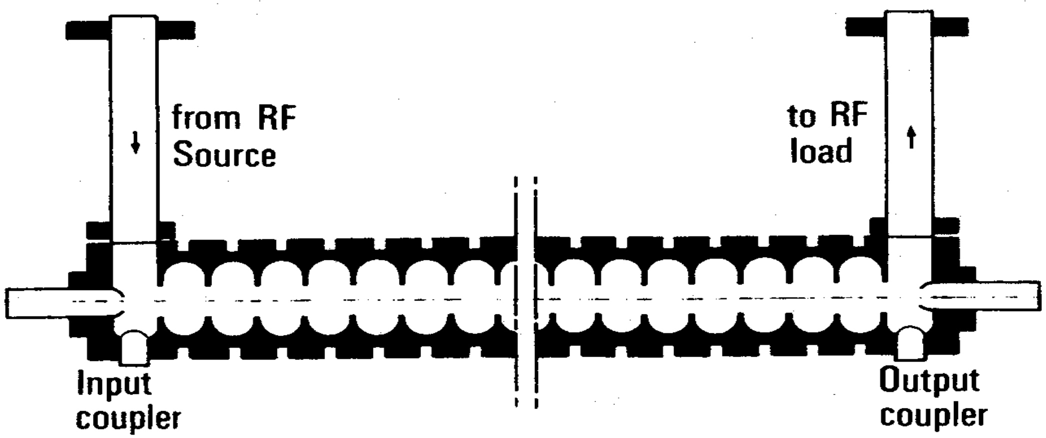
These cavities are essentially used for acceleration of ultra-relativistic particles.
The longitudinal field component is:

$$E_z(r,z,t)=\sum E_n(r)\cdot e^{j(\omega t-k_n z)}$$

$E_n(r)\cdot e^{j(\omega t-k_n z)}$ is a space harmonic of the field, given by the cavity periodicity

Particle whose velocity is close to the phase velocity of the space harmonic exchanges energy with it. Otherwise, mean effect is null.



Constant cell length does not allow synchronism
Structures are long without space for transverse focusing

Cavity parameters

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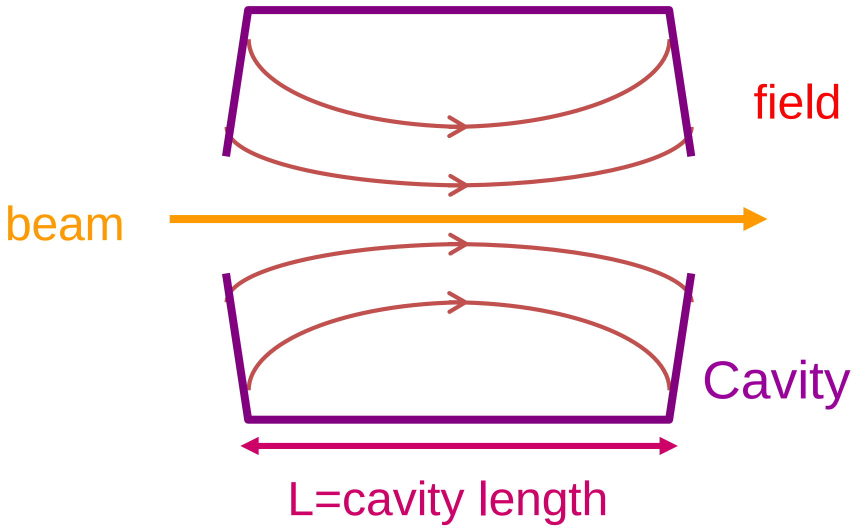

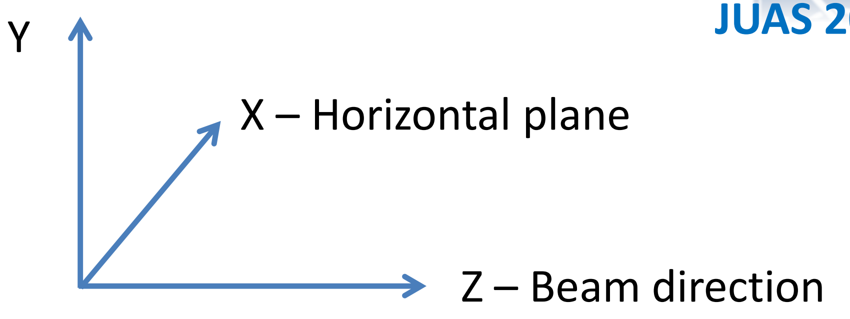

1. Average electric field
2. Shunt impedance
3. Quality factor
4. Filling time
5. Transit time factor
6. Effective shunt impedance

Average electric field

Average electric field: **E_0** measured in V/m.

Average electric field on beam axis in the direction of the beam propagation at a given moment in time when E(t) is maximum.

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

x=0, y=0, z from 0 to L (cavity length)

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

Measure how much field is available for acceleration

Depends on the cavity shape, resonating mode and frequency

Shunt impedance

Shunt impedance (per unit of length): **Z** measured in Ω/m.
Defines the ratio of the average electric field squared (E_0^2) to the power (P) per unit of length (L) dissipated on the walls surface.

$$Z = E_0^2 . \frac{L}{P} \quad or \quad Z = E_0^2 . \frac{dL}{dP}$$

Measure how well we concentrate the RF power in the useful region.
Independent on the field level and cavity length. Depends on cavity mode and geometry.

Quality factor

Quality factor: **Q** dimension-less.
Defines the ratio of the stored energy (U) to the power lost on the wall (P) in one RF cycle (f = frequency).

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

Q is a function of the geometry and of the surface resistance of the cavity material.

Examples at 700 MHz

Superconducting (niobium): $Q=10^{10}$ (depends on temperature)
Normal conducting (copper): $Q=10^{4}$ (depends on cavity mode)

Filling time

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Filling time: t_F measured in sec.
Two different definition for traveling or standing wave.

- For TW: 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 propagate thru the cavity

- For SW: Time it takes for the field to decrease by 1/e after the cavity has beam filled.

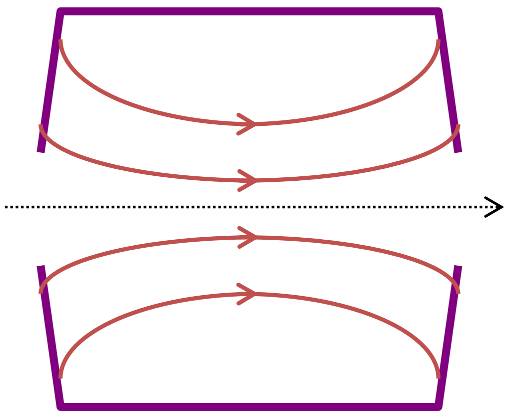
$$t_F = \frac{2Q}{\omega}$$

How fast the stored energy is dissipated to the wall

Transit time factor

Transit time factor: **T** dimension-less.
Defines the ratio of the energy gained in the time varying RF field to that in a DC field.
T is a measure of the reduction in energy gain caused by the sinusoidal time variation of the field in the gap.

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



Energy gain of a particle with charge q on axis at phase ϕ.

$$\Delta W = \int_0^L qE_z(0,0,z).e^{-j(\omega t+\phi)}dz$$

Transit time factor

Assuming a constant velocity thru the cavity (approximation!!!), we can relate position and time via

$$Z = v.t = \beta c.t$$

We can write the energy gain as

$$\Delta W = q.E_0.L.T.\cos(\phi)$$

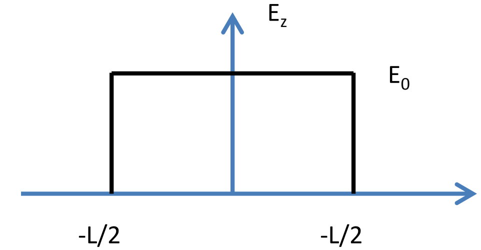
And define transit time factor as

$$T = \frac{\int_{-L/2}^{L/2} E_z(z).e^{-j\left(\frac{\omega z}{\beta c}\right)} dz}{\int_{-L/2}^{L/2} E_z(z).dz} = \frac{\int_{-L/2}^{L/2} E_z(z).e^{-j\left(\frac{\omega z}{\beta c}\right)} dz}{E_0 L}$$

T depends on the particle velocity and on the gap length.
It does not depend on the field.

Transit time factor

NB: TTF depends on x and y (distance for the beam axis in cylindrical symmetry.
By default, TTF is on axis!



Exercise:

Calculate the TTF for a pillbox cavity where E_z=E_0

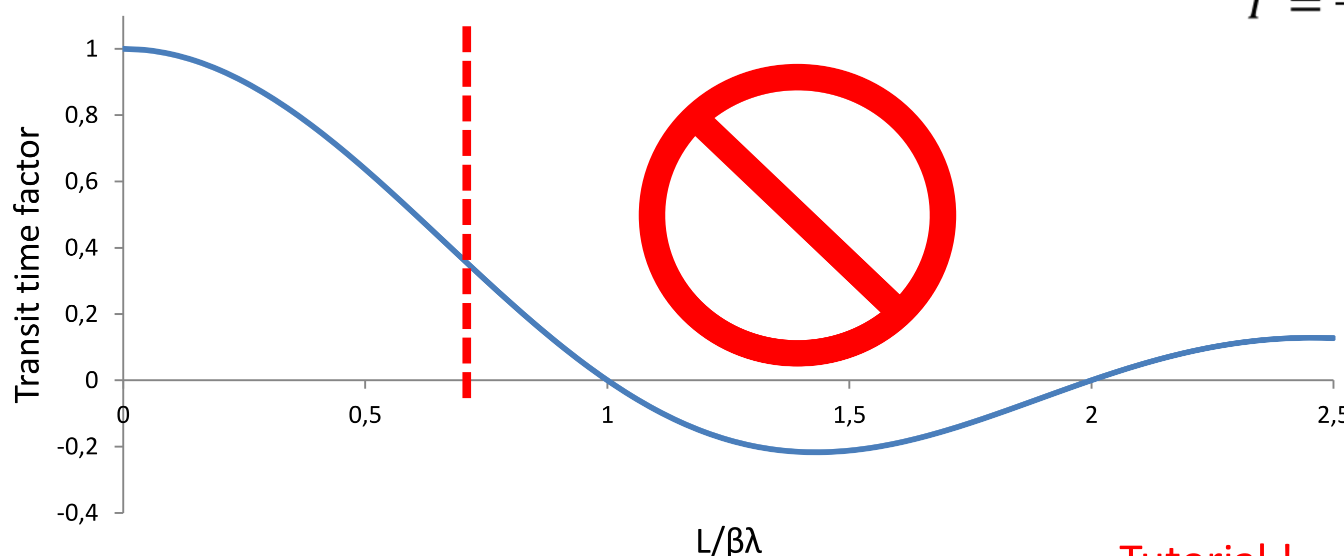
L=gap length

β= reduced velocity

λ= RF wavelength

Distance travelled during on RF period: βc/f = βλ

$$T = \frac{\sin\frac{\pi L}{\beta\lambda}}{\frac{\pi L}{\beta\lambda}}$$



Tutorial !

Effective shunt impedance

Effective shunt impedance: **ZT^2**.
More practical for accelerator designers who want to maximize the particle energy gain per unit power dissipation.

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

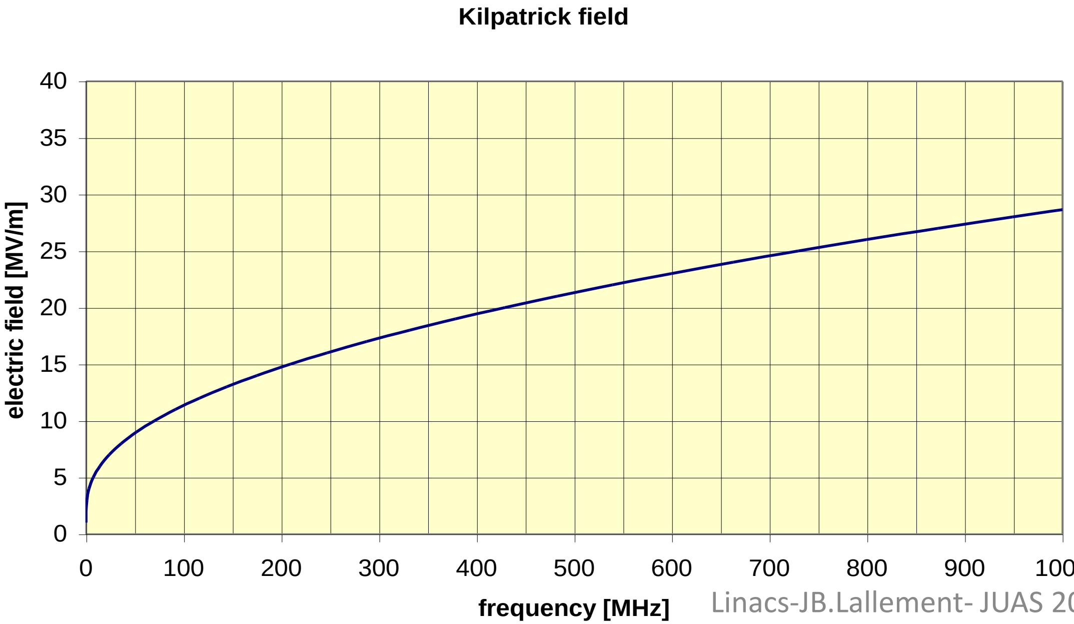
While the shunt impedance measures if the structure design is optimized,
the effective shunt impedance measures if the structure is optimized and adapated to the velocity of the particle to be accelerated.

Limit to the field in a cavity

- Normal conducting
  - Heating
  - Electrical peak surface field (sparking)
- Super conducting
  - Quenching
  - Magnetic field on the surface (in Niobium max 200 mT)

The Kilpatrick sparking criterion

Normal conducting – Large gap



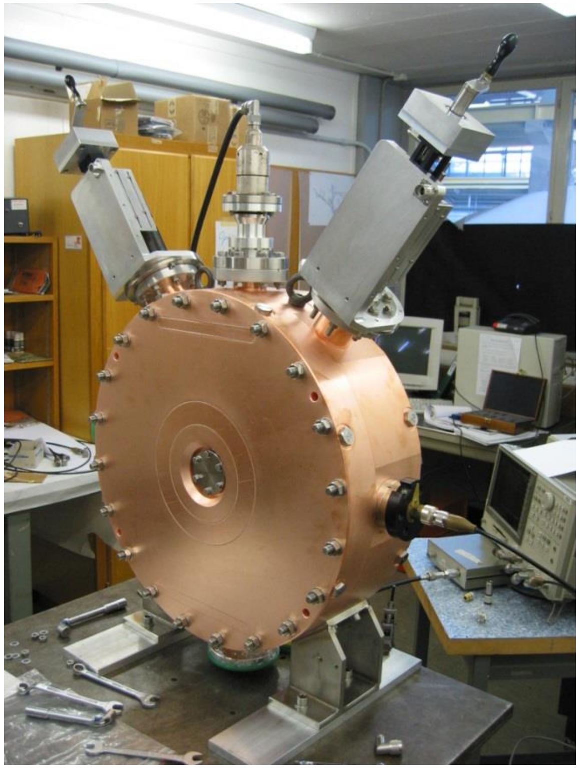
$$f = 1.64 * E^2 * \exp\left(\frac{-8.5}{E}\right)$$

W.D. Kilpatrick in the 50’s

Nowadays, the peak surface field up to 2 Kilpatrick

Tutorial !

Example of cavities



Summary of Part1

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First step to accelerating is to fill a cavity with electromagnetic energy to build a resonant field. In order to be the most efficient, one should:

- Concentrate the field in the beam area
- Minimize losses of RF power
- Control the limiting factors to put energy into the cavity

The is achieved by shaping the cavity in the appropriate way