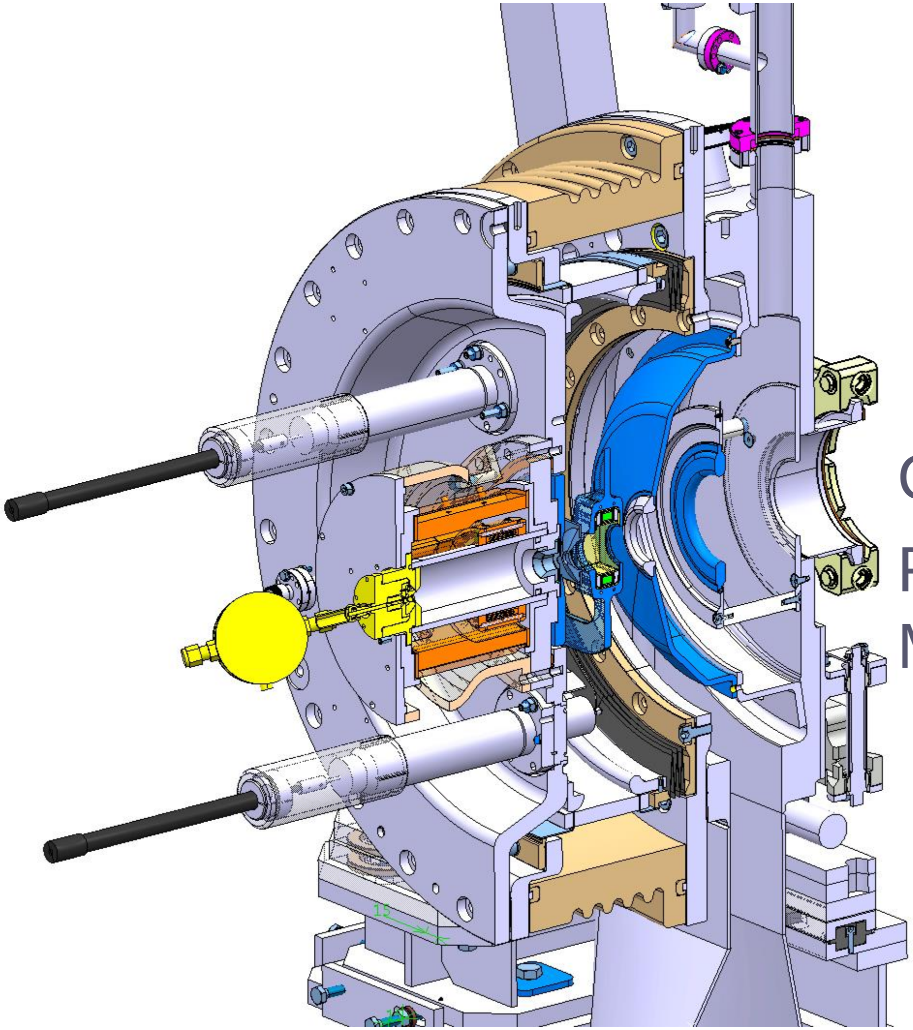
TECHNOLOGY OF PARTICLE ACCELERATORS



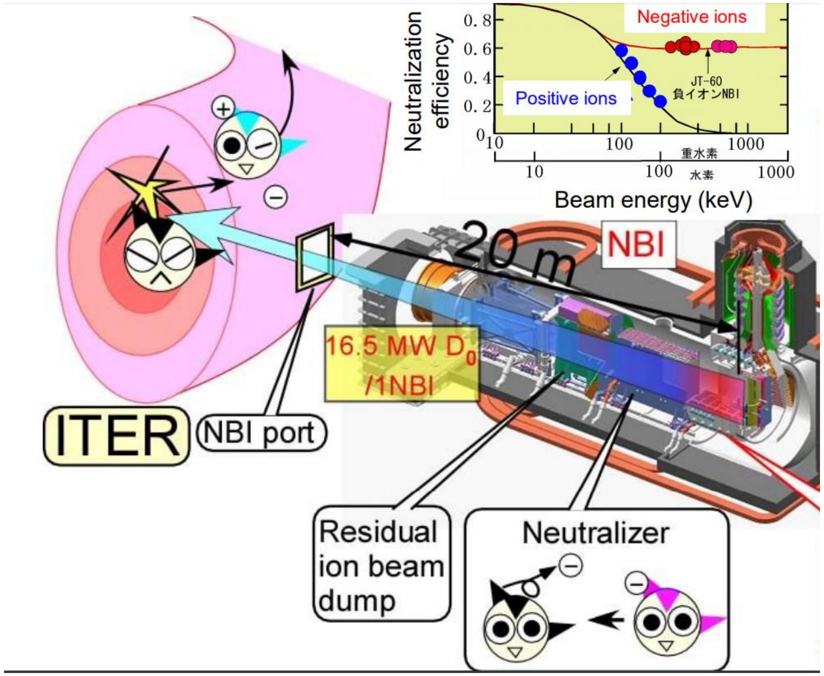
Cristhian Alfonso Valerio Lizarraga

Facultad de ciencias Físico Matemáticas

Why ?

- There are many kinds of projects that need accelerators.
- The users will define the needs of the machine.

Tokamak injection



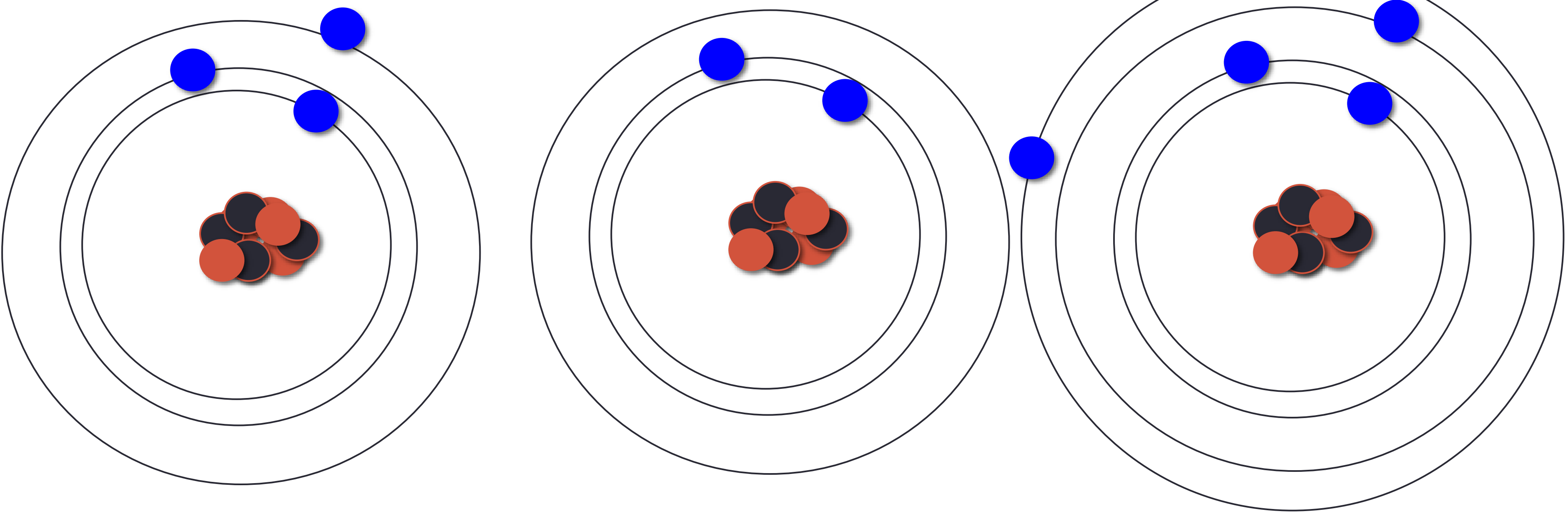
M. Kashiwagi and M. Hanada NB heating Tech Gr., Naka-fusion Institute, Japan Atomic Energy Agency (JAEA)

Water irradiation

Comparison of wastewater before (left) and after (right) electron beam radiation.
(Photo: Nuclear and Energy Technology Institute, Tsinghua University)

The fundamental blocks: Charged Particles

● Electrons ● Positron ● Protons ● AntiProtons



Positive Ions :
1 o more electrons
are removed

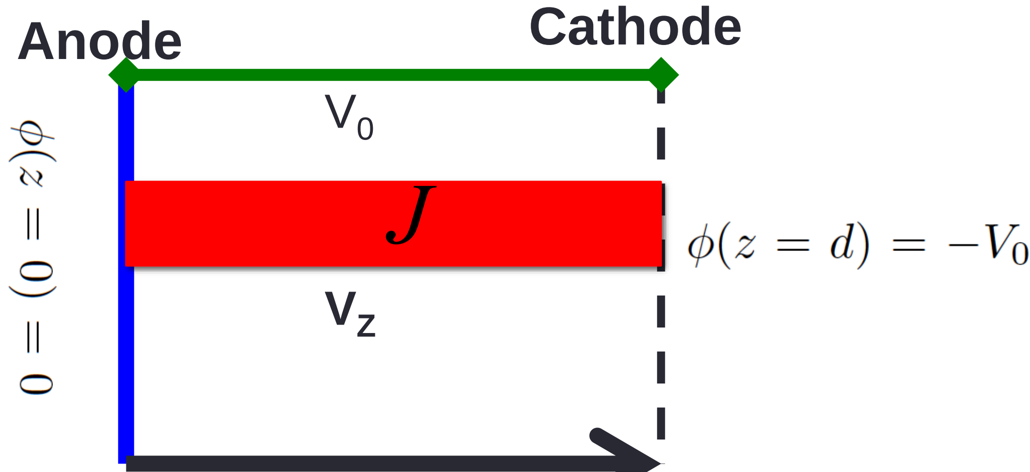
Negative Ions :
A extra electron Is
attached

Ion and electron generation

Particles	Generation form
Ions	Surface production Plasma production
Electrons	Photo emission Thermal emission

- Quantum dynamics is necessary to understand and improve the particles production.
- Electrons usually arise from a surface(cathode)

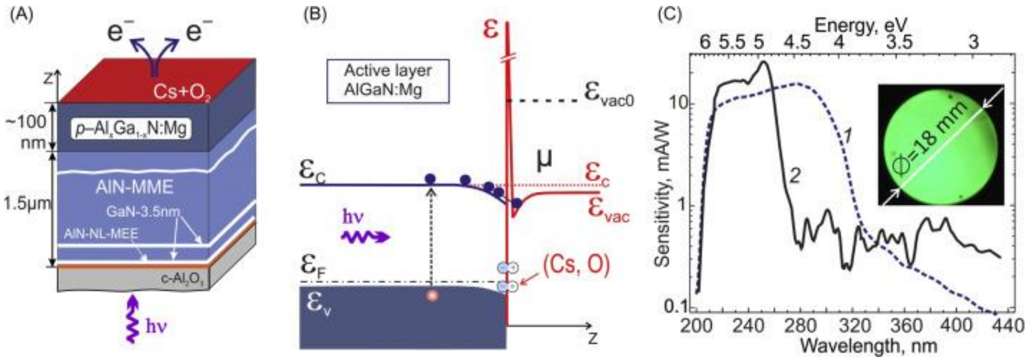
$$\frac{M_p}{M_e} = \frac{937mev}{.511mev} \gg 1836$$

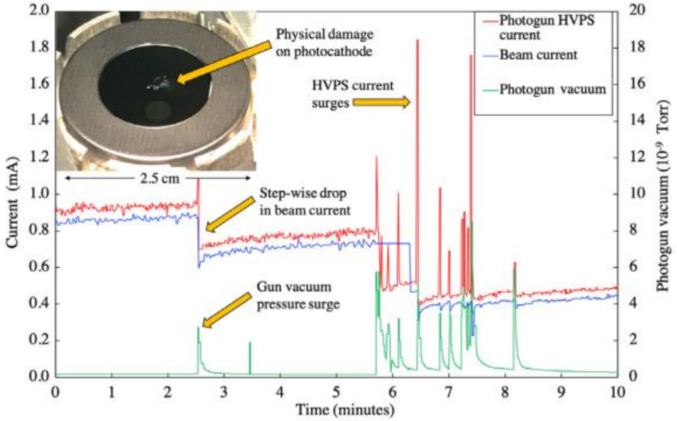


Electron Photo emission

- Semiconductors
- Is possible to find materials with optical wavelengths with high Q.E
- GaAs.Cs has high QE at 532nm
- They need constant treatments
- METALS
- The quantum efficiency is low
- Very reliable in operation

1 A intensity in 1 mm^2

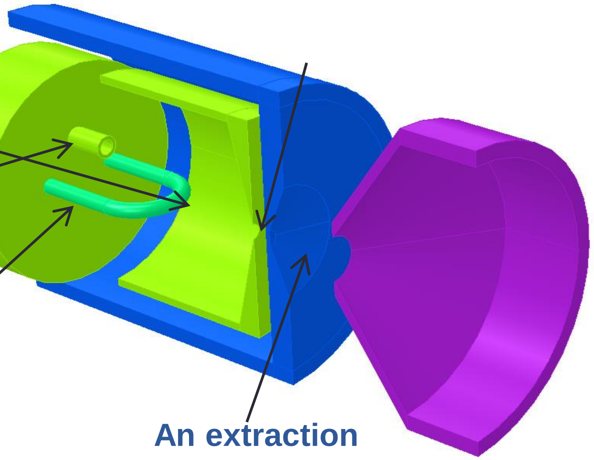




Nature Gaoxue Wang

Ion Source

The beam is formed by the particles in the plasma taken by the extractor



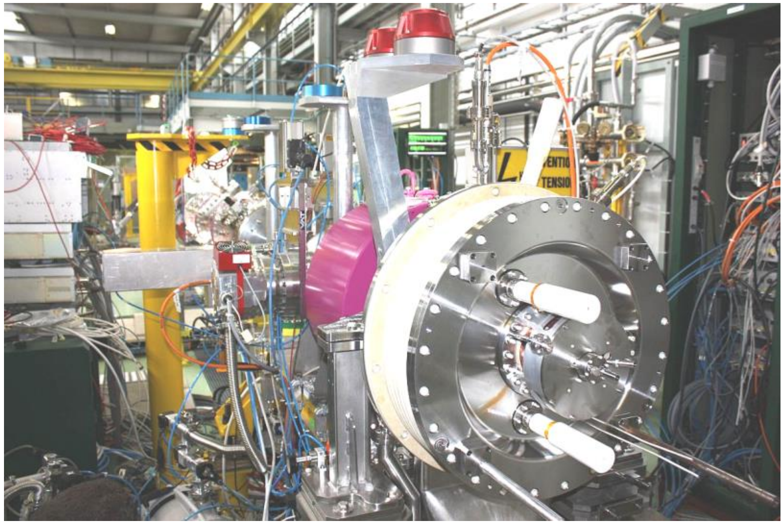
A hole to let the ions out!

A plasma or discharge chamber

Material input

Power to create a plasma / discharge

An extraction system

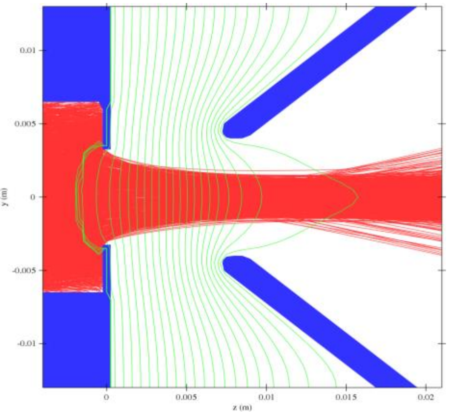


$$E = q(V_{source} - V_{ground})$$

Plasma extraction potential (meniscus)

Ground

Extracto



Plasma

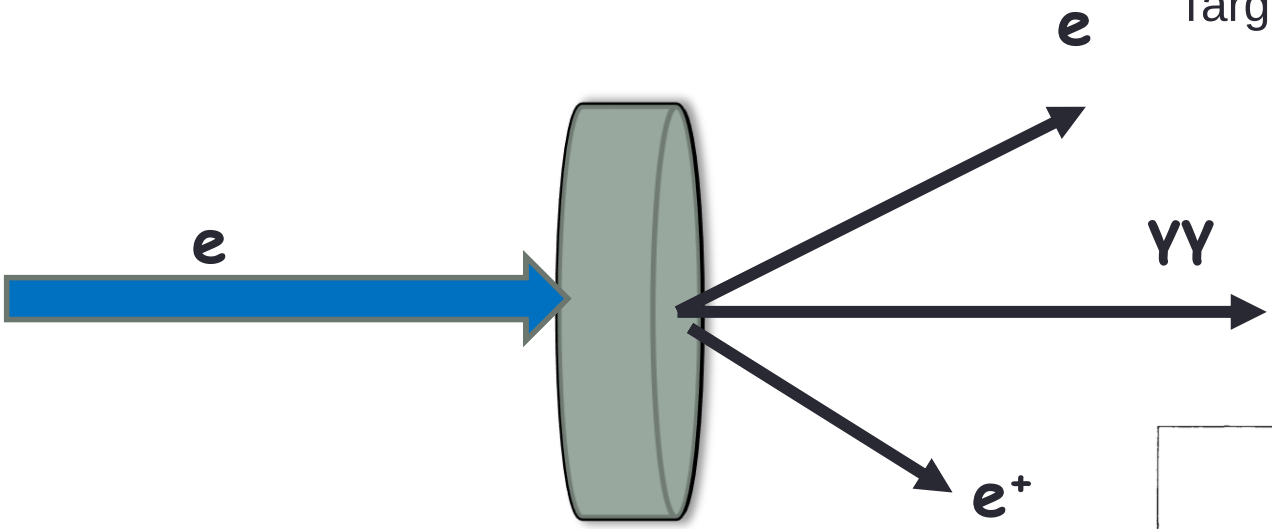
Potential lines(green)
Electrodes (blue)

Ion Beam

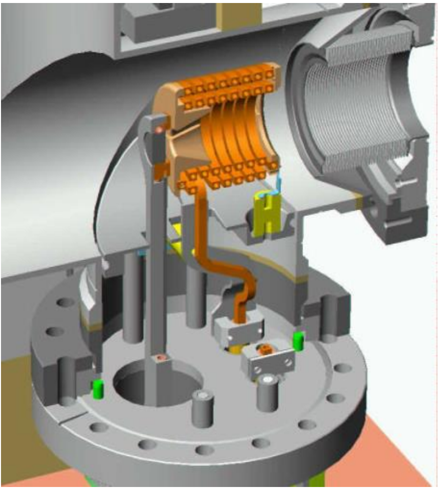
Ions (Red)

Antimatter!

- Positrons are commonly used in high energy physics experiments

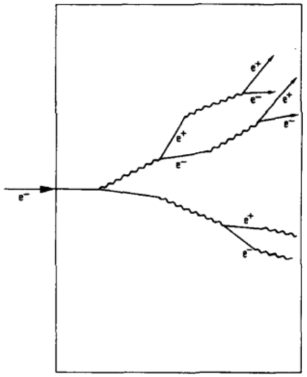


W Target



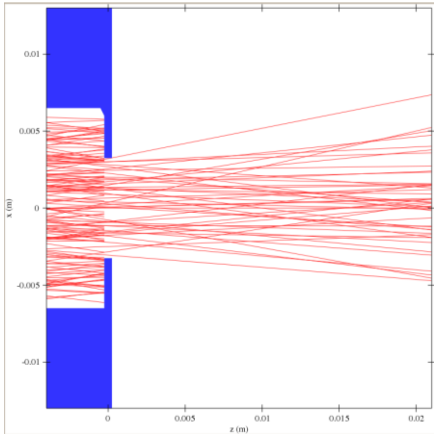
Focusing coil with flux concentrator

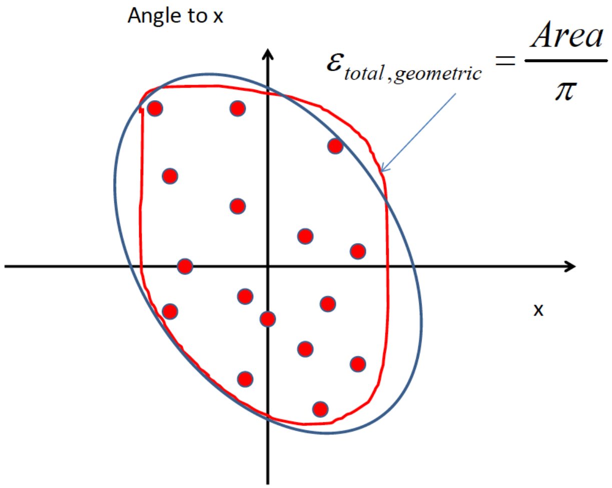
Bremsstrahlung is the main generator of positrons
Difficult to collect



Emittance

- The region in phase space that the particles in a beam occupy is called the beam emittance





- Mm.mrad? mrad from p_x/p_z
- The goal in every accelerator is to have the lower beam emittance achievable

$$e = \frac{r}{2c}\sqrt{\frac{kT}{m}} \mu T^{1/2} \qquad Brighness \mu \frac{1}{e_y e_x}$$

Time structure

The beam time structure is also an important parameter in the particles source

- Beam pulse length is defined as

$$T_{pulse}$$

- The repetition rate is defined by the number of pulses in a second

$$\frac{1}{T_{rep}}$$

- The duty factor is defined as

$$Dutyfactor = \frac{T_{pulse}}{T_{rep}}$$

Beam Intensity

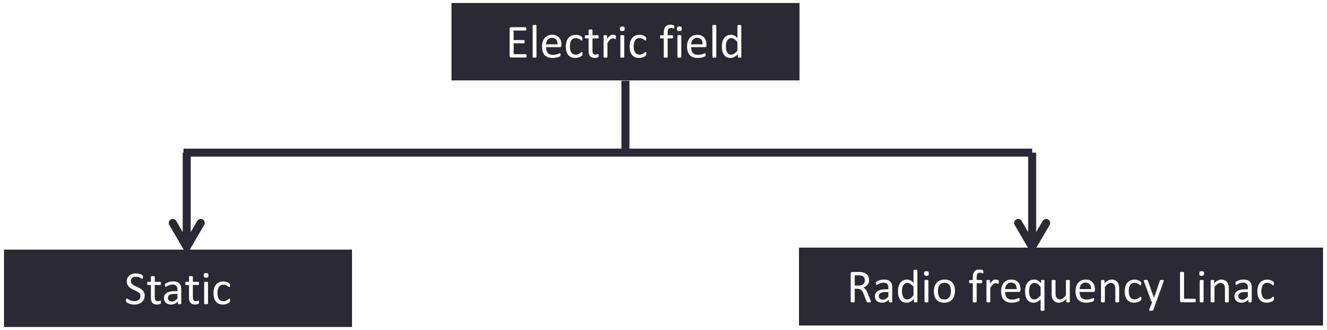
- The source intensity is measured in terms of
- beam current.
- Total charge taking in to account beam pulse time structure
- Number of particles in the beam

$$I_{beam} = \frac{qeN_{ions}}{t}$$

q= particle charge

e= electron charge

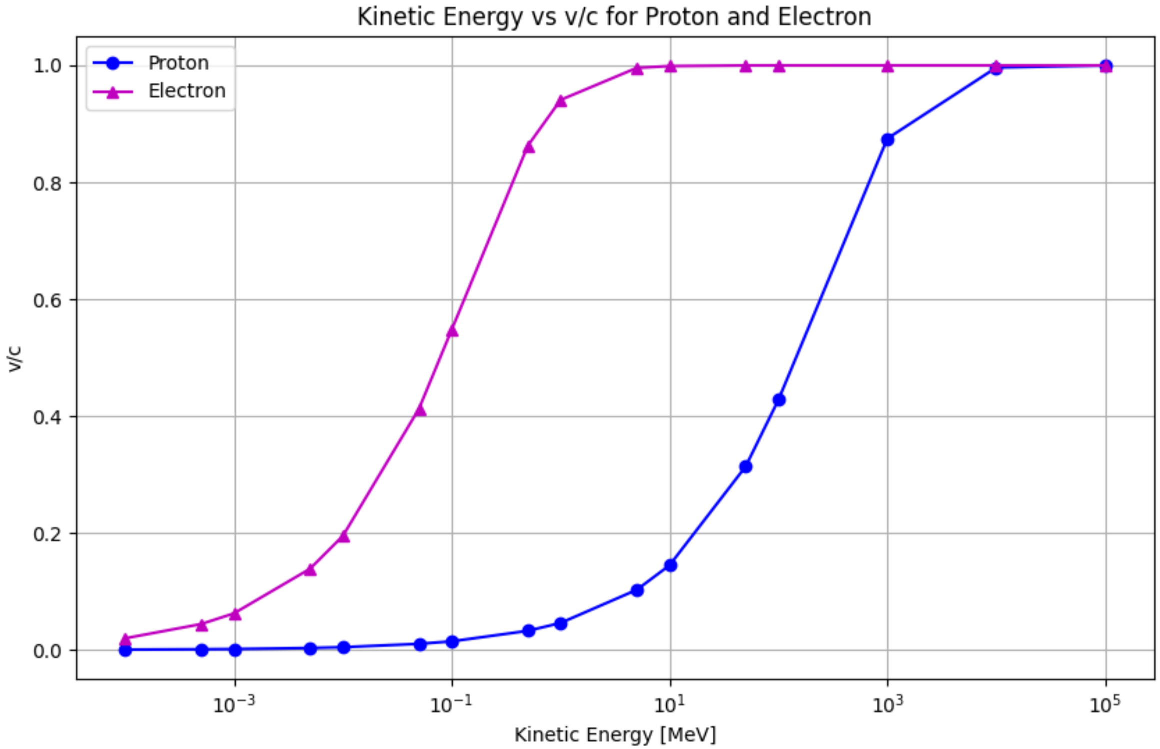
Different type of LINACs



Electric field

Static

Radio frequency Linac



Protons don't get relativistic up to high energies

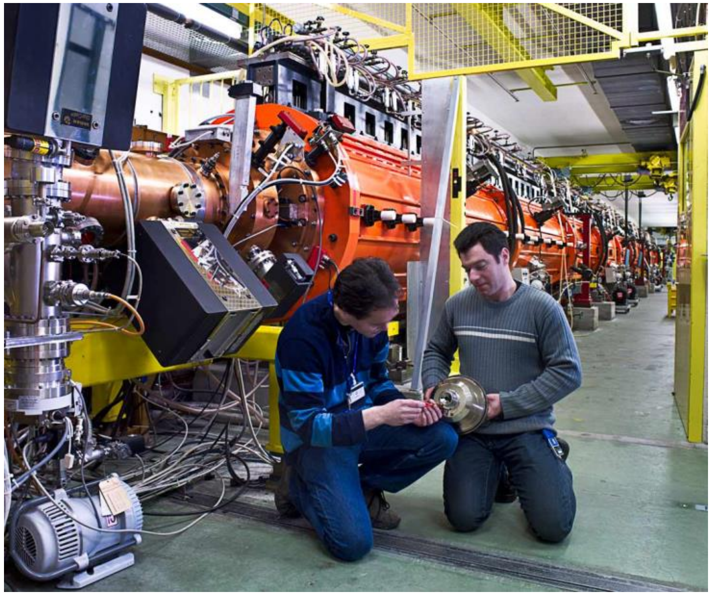
Static vs RF Linac

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

Energy limited by the maximum voltage that can be applied somewhere (MV at most).

Still used in very first stage of acceleration.
(Fermilab stopped using their's in 2012.)

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



Principle RF Linacs

- The electric field of an RF wave is used for acceleration.

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

- So the wave is trapped in the cavity.

Standing Wave

(This is the lecture topic)

Traveling Wave

RF acceleration

1. RF power source

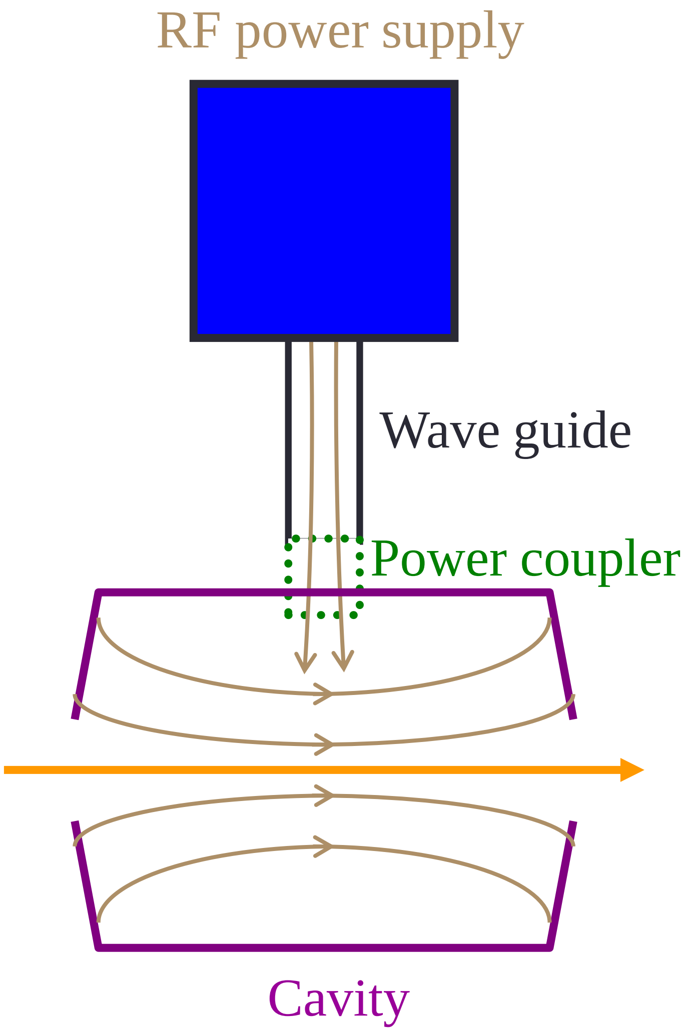
   Generator of electromagnetic wave of a specified frequency

2. Cavity

   Space enclosed in a metallic boundary which resonates with the wave frequency and tailors the field pattern
3. Beam

   Flux of particles going thru the cavity.
4. Energy gain

   Field and phase is adjusted to accelerate the beam.



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

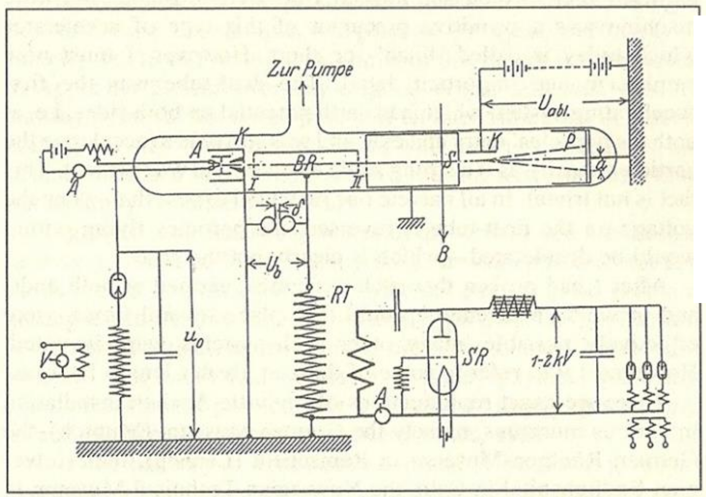
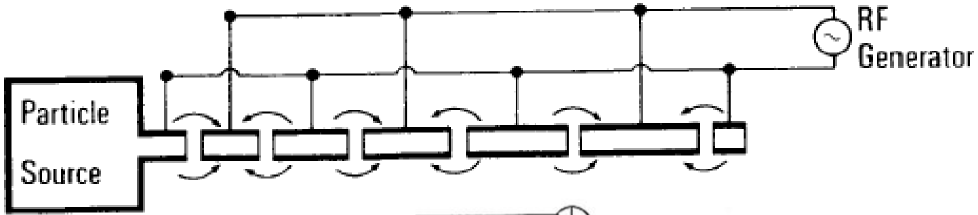
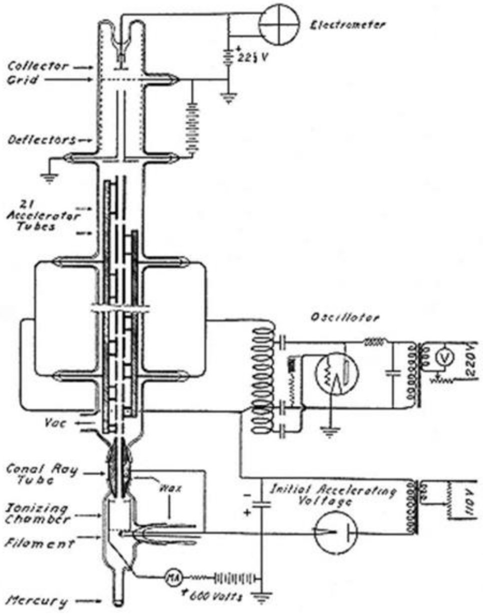


Fig. 3.6: Acceleration tube and switching circuits [Wi28].





First working Linac – Berkeley in 1931

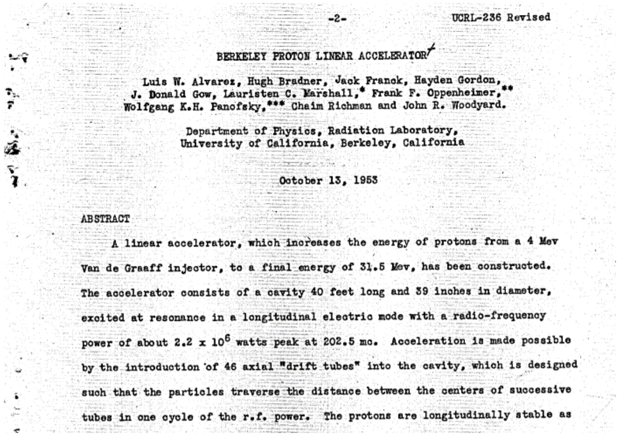
Hg beam – 30*42 kV = 1.26 MeV

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
- Large numbers of 202MHz power sources were available
- First Drift Tube Linac in 1953 from 4 to 32 MeV.



-2- UCRL-236 Revised

BERKELEY PROTON LINEAR ACCELERATOR†

Luis W. Alvarez, Hugh Bradner, Jack Franck, Hayden Gordon,
J. Donald Gow, Lauristen C. Marshall,* Frank F. Oppenheimer,**
Wolfgang K.H. Panofsky,*** Chaim Richman and John R. Woodyard.

Department of Physics, Radiation Laboratory,
University of California, Berkeley, California

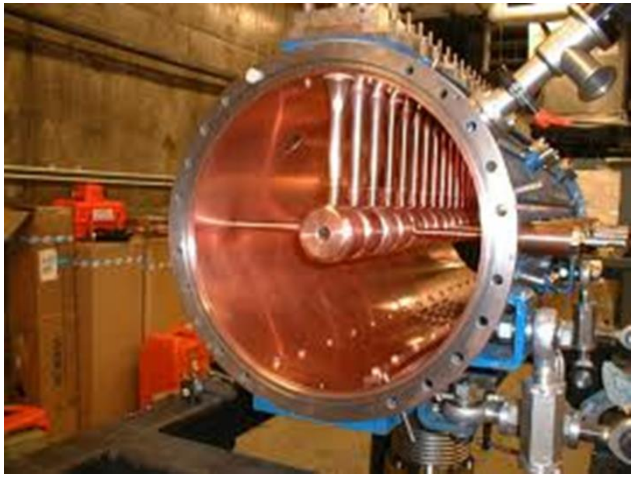
October 13, 1953

ABSTRACT

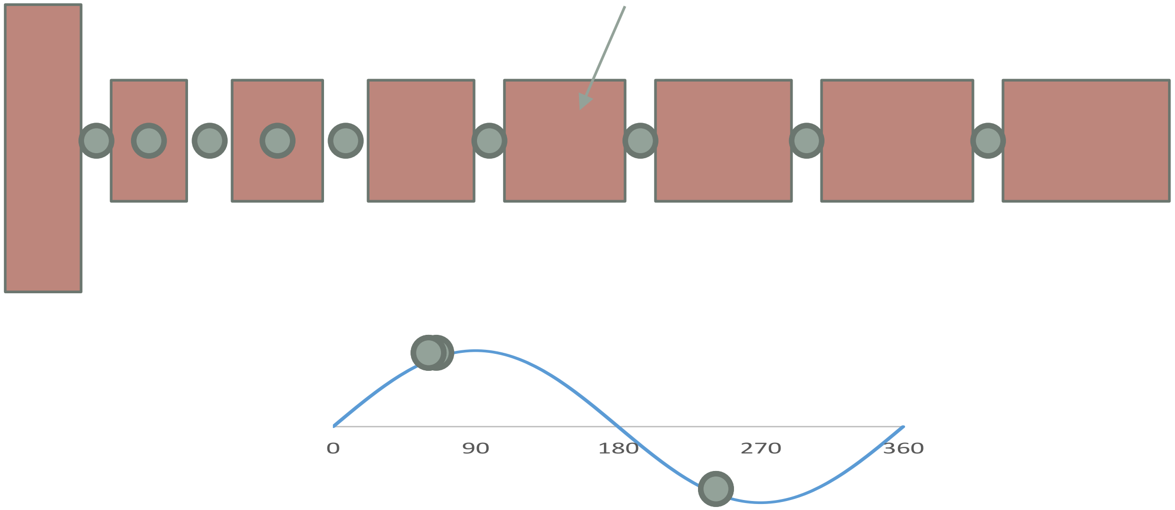
A linear accelerator, which increases the energy of protons from a 4 Mev Van de Graaff injector, to a final energy of 31.5 Mev, has been constructed. The accelerator consists of a cavity 40 feet long and 39 inches in diameter, excited at resonance in a longitudinal electric mode with a radio-frequency power of about 2.2 x 10^6 watts peak at 202.5 mc. Acceleration is made possible by the introduction of 46 axial "drift tubes" into the cavity, which is designed such that the particles traverse the distance between the centers of successive tubes in one cycle of the r.f. power. The protons are longitudinally stable as

Basis of modern RF Linac technology !!!

http://www.osti.gov/accomplishments/documents/fullText/ACC0212.pdf



Standing Wave Cavities - Synchronization

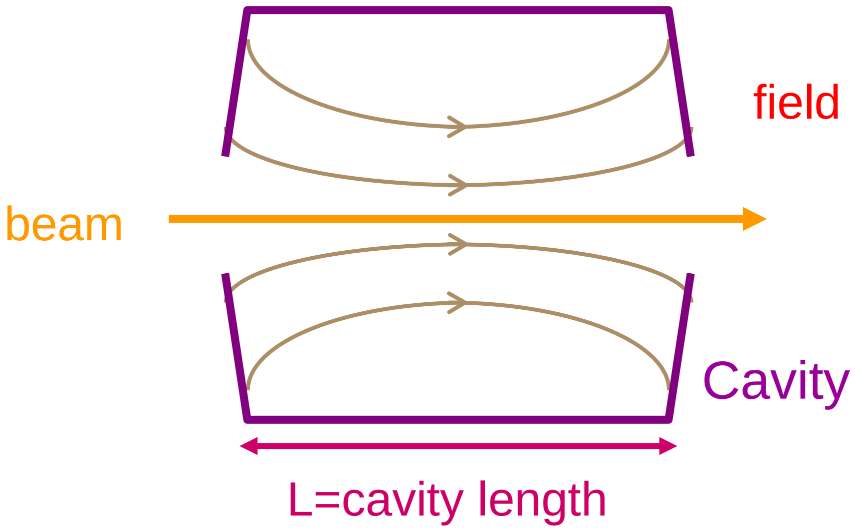

Drift tubes with holes for beam passage

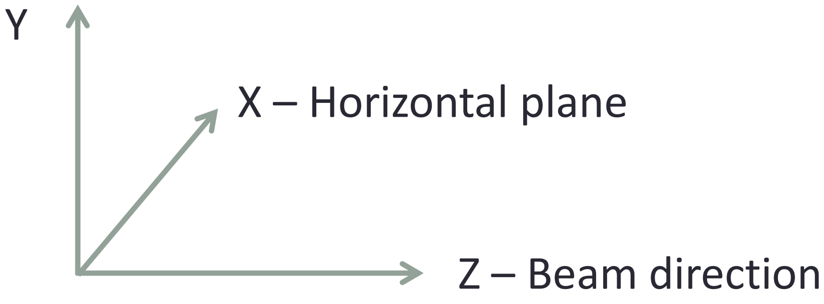
Particles are hidden inside the tubes when the field is in the wrong direction.

Synchronize the transit time from one gap to the next with the RF oscillation.

Particles must follow the correct velocity at each point in Linac.

Cavity parameters





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

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

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

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

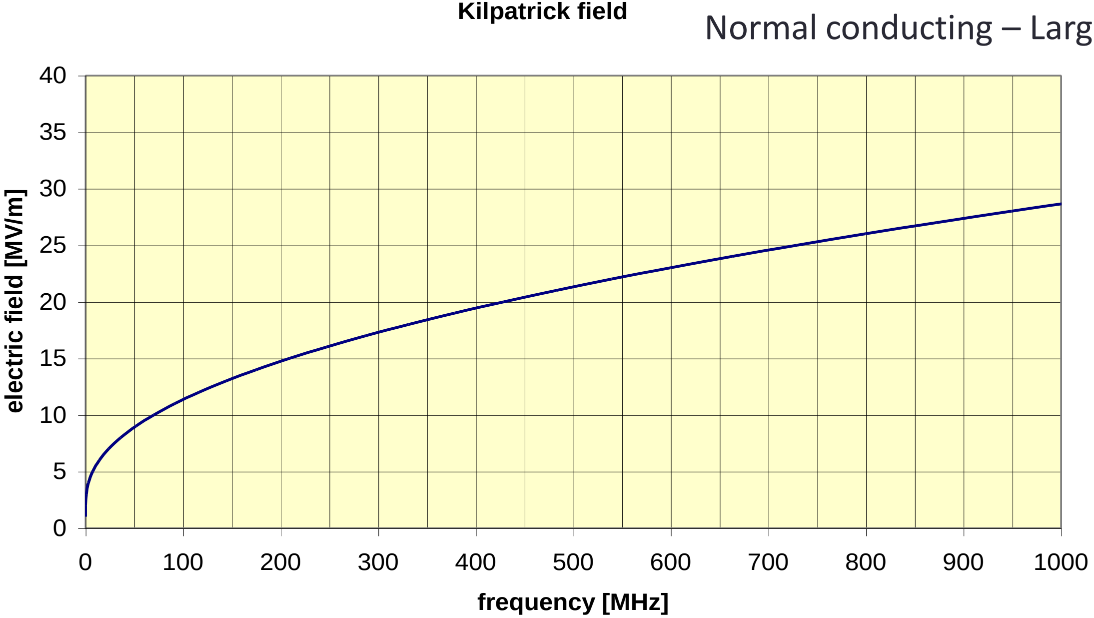
Limit to the field in a cavity

- 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



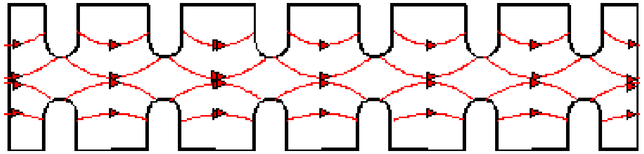
$$f = 1.64 * E^2 * \exp\left(\frac{-8.5}{E}\right)$$

Measured by W.D. Kilpatrick in the 50's

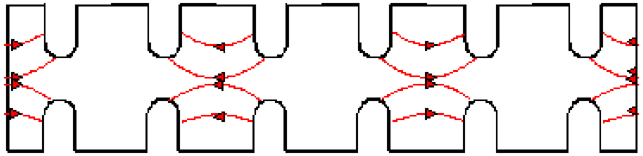
Nowadays, the peak surface field up to 2 Kilpatrick

Example of cavities

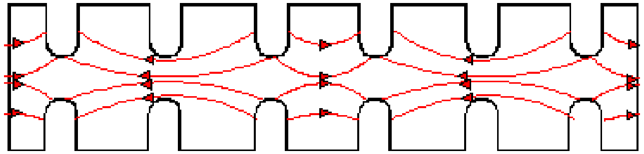
Standing Wave Modes



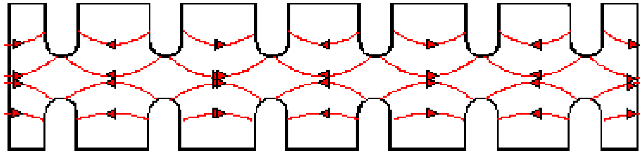
mode 0



mode π/2



mode 2π/3



mode π

Named from the phase differenc between adjacent cells.

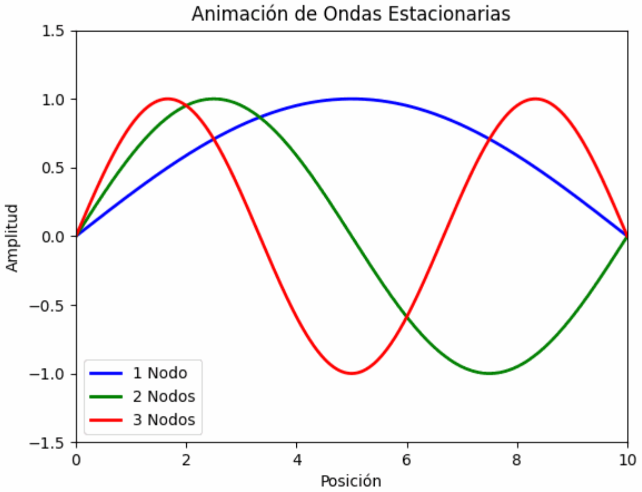
Mode 0 also called mode 2π.

For synchronicity and acceleration, particles must be in phase with the E field on axis (will be discussed more in details in part.3).

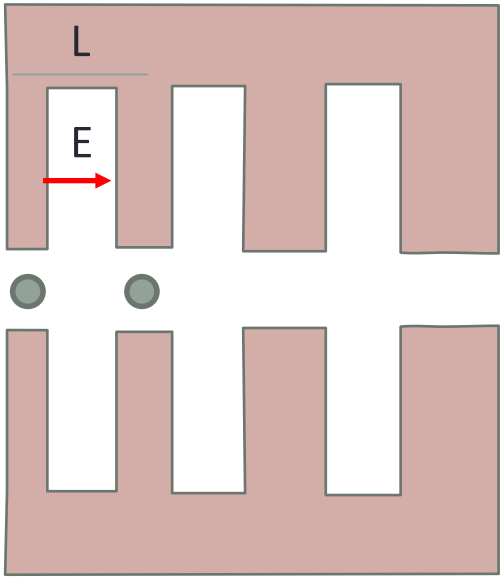
During 1 RF period, the particles travel over a distance of βλ.

The cell L length should be:

Mode	L
2π	βλ
π/2	βλ/4
2π/3	βλ/3
π	βλ/2



How To Synchronise



Our particle enters the first acceleration gap with energy W_0.

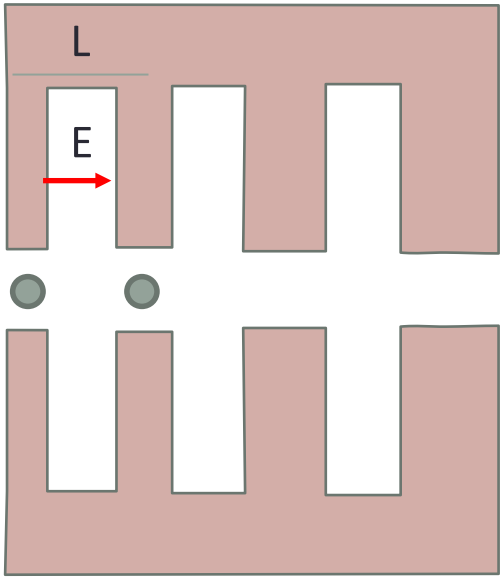
In crossing the first accelerating gap our particle gains energy.

$$\Delta W = qELT\cos(\varphi)$$

Tutorial Question!

$$W_1 = W_0 + \Delta W$$

How To Synchronise



The time to cross the first gap is given by the average energy.

$$\Delta t = L/c\beta\left(W + \frac{\Delta W(L)}{2}\right)$$

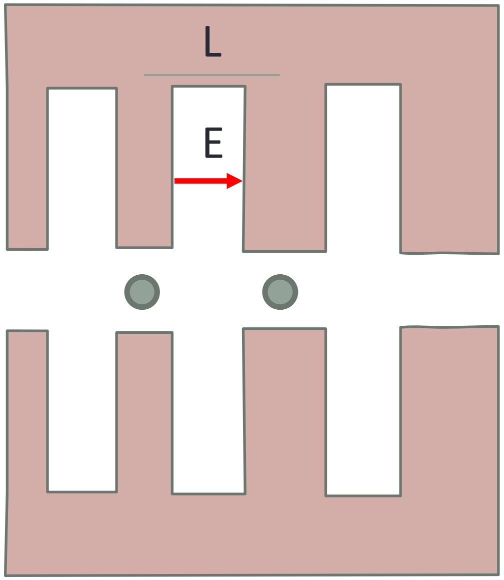
But the time to cross the gap is fixed by the RF frequency

$$1/\Delta t = f$$

How To Synchronize

So the value of L has to be calculated from this this constraint.

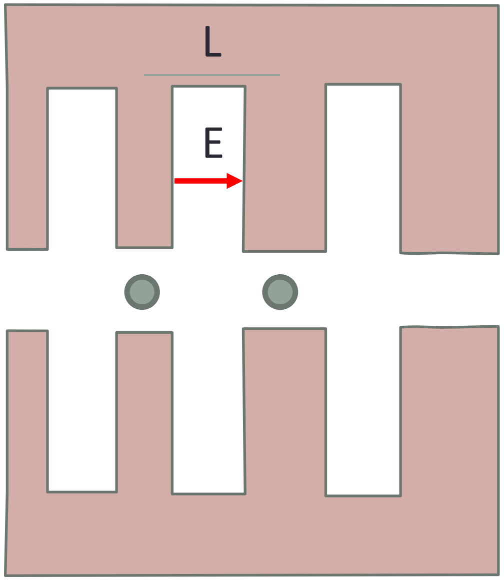
$$1/f = L/c\beta(W_0 + \frac{\Delta W(L)}{2})$$



And for the second gap we repeat the same exercise.

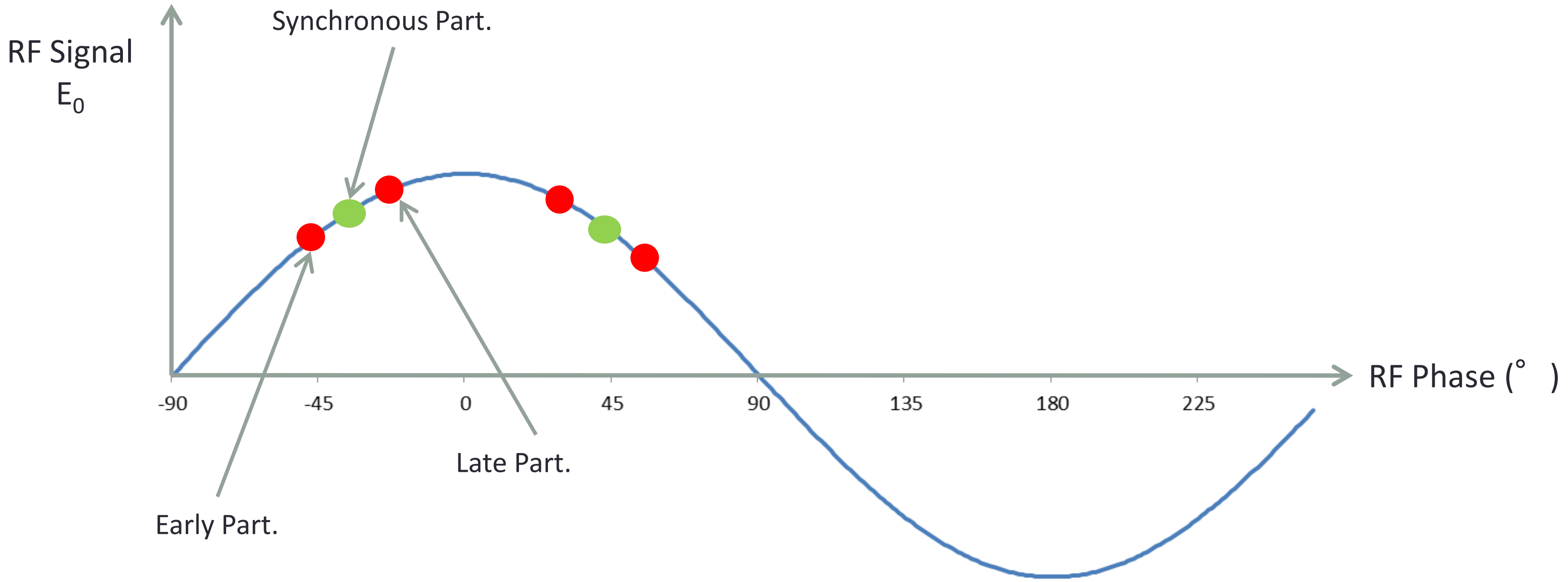
How To Synchronize

We also see from this that the particles must remain velocity matched along our cavity structure, and the design is fixed once it is built.



So if the particle type is changed, and as the frequency cannot be changed, the fields must be scaled to keep at the correct velocity at all points.

Bunching



Energy gain for the synchronous particle $\Delta W_s = qE_0LT\cos(\phi_s)$

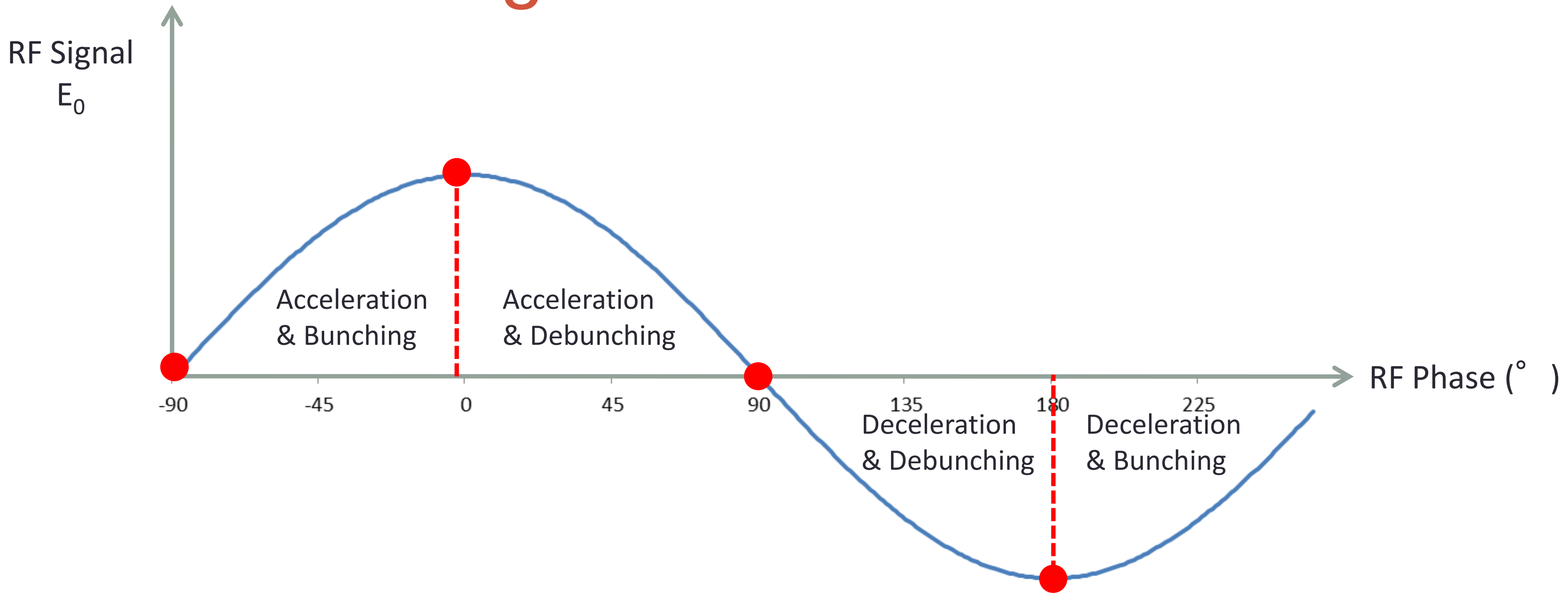
Energy gain for a particle with phase ϕ $\Delta W = qE_0LT\cos(\phi)$

$$\frac{d}{ds}\Delta W = qE_0T\cdot[\cos(\varphi_s+\Delta\varphi)-\cos\varphi_s]$$

For $\phi-\phi_s$ small

$$\frac{d}{ds}\Delta\varphi = \omega\left(\frac{dt}{ds}-\frac{dt_s}{ds}\right)=\frac{\omega}{c}\left(\frac{1}{\beta}-\frac{1}{\beta_s}\right)\cong-\frac{\omega}{\beta_s c}\frac{\Delta\beta}{\beta_s}=-\frac{\omega}{mc^3\beta_s^3\gamma_s^3}\Delta W$$

Bunching



Energy gain for the synchronous particle

$$\Delta W_s = qE_0 LT\cos(\phi_s)$$

Energy gain for a particle with phase ϕ

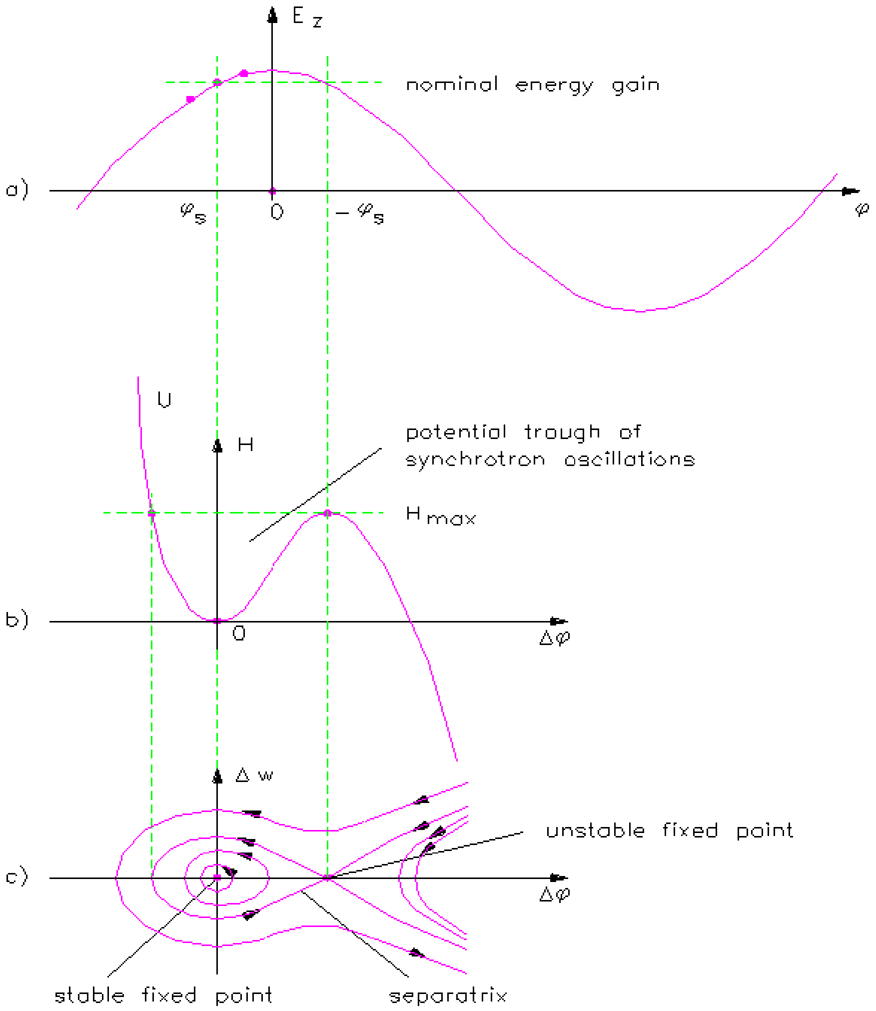
$$\Delta W = qE_0 LT\cos(\phi)$$

$$\frac{d}{ds}\Delta W = qE_0 T\cdot[\cos(\varphi_s + \Delta\varphi) - \cos\varphi_s]$$

For ϕ-ϕ_s small

$$\frac{d}{ds}\Delta\varphi = \omega\left(\frac{dt}{ds} - \frac{dt_s}{ds}\right) = \frac{\omega}{c}\left(\frac{1}{\beta} - \frac{1}{\beta_s}\right) \cong -\frac{\omega}{\beta_s c}\frac{\Delta\beta}{\beta_s} = -\frac{\omega}{mc^3\beta_s^3\gamma_s^3}\Delta W$$

Separatrix



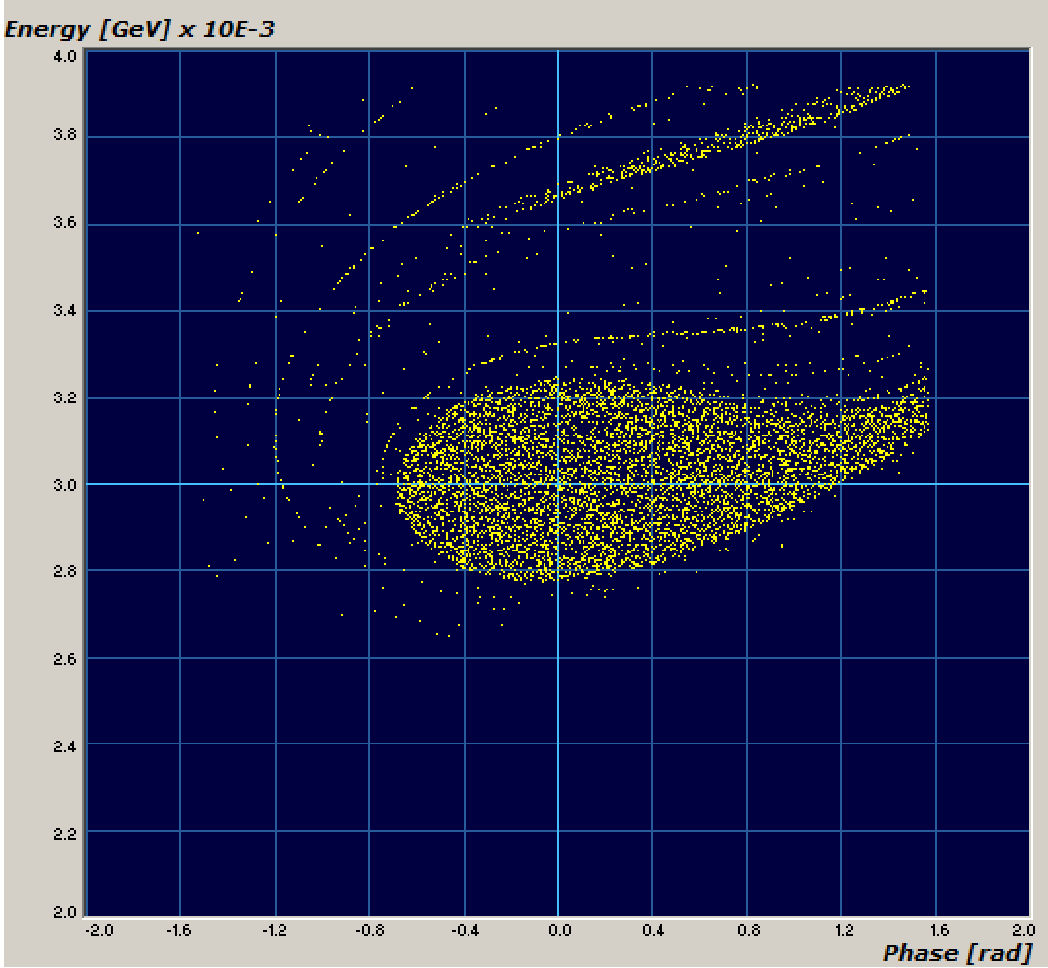
RF electric field as function of phase.

Potential of synchrotron oscillations

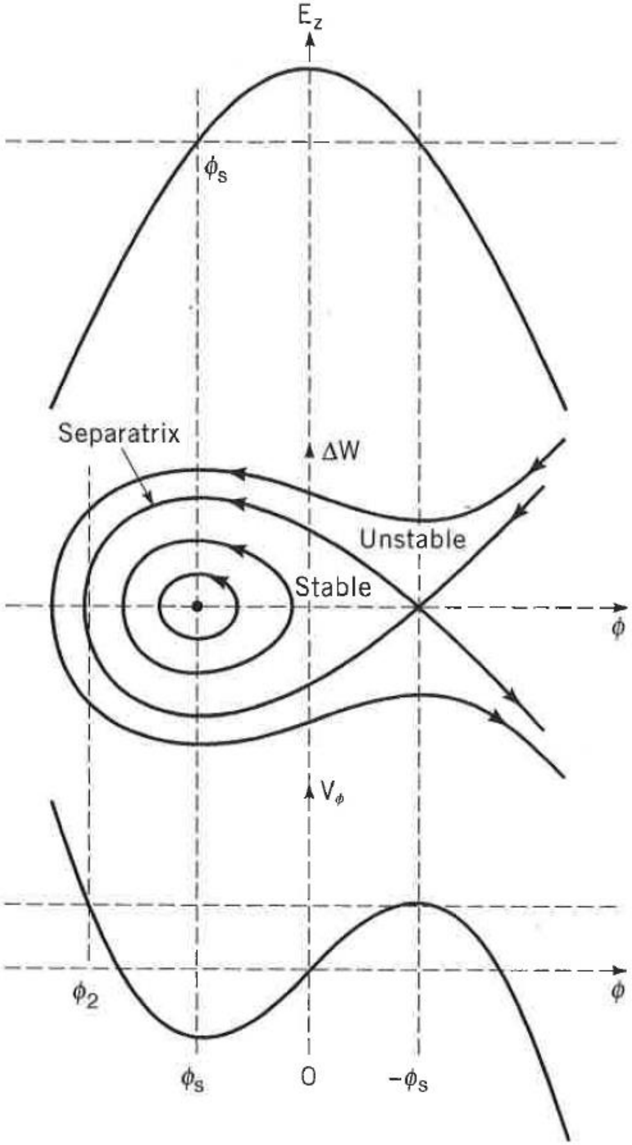
Trajectories in the longitudinal phase space each corresponding to a given value of the total energy (stationary bucket)

Tutorial !

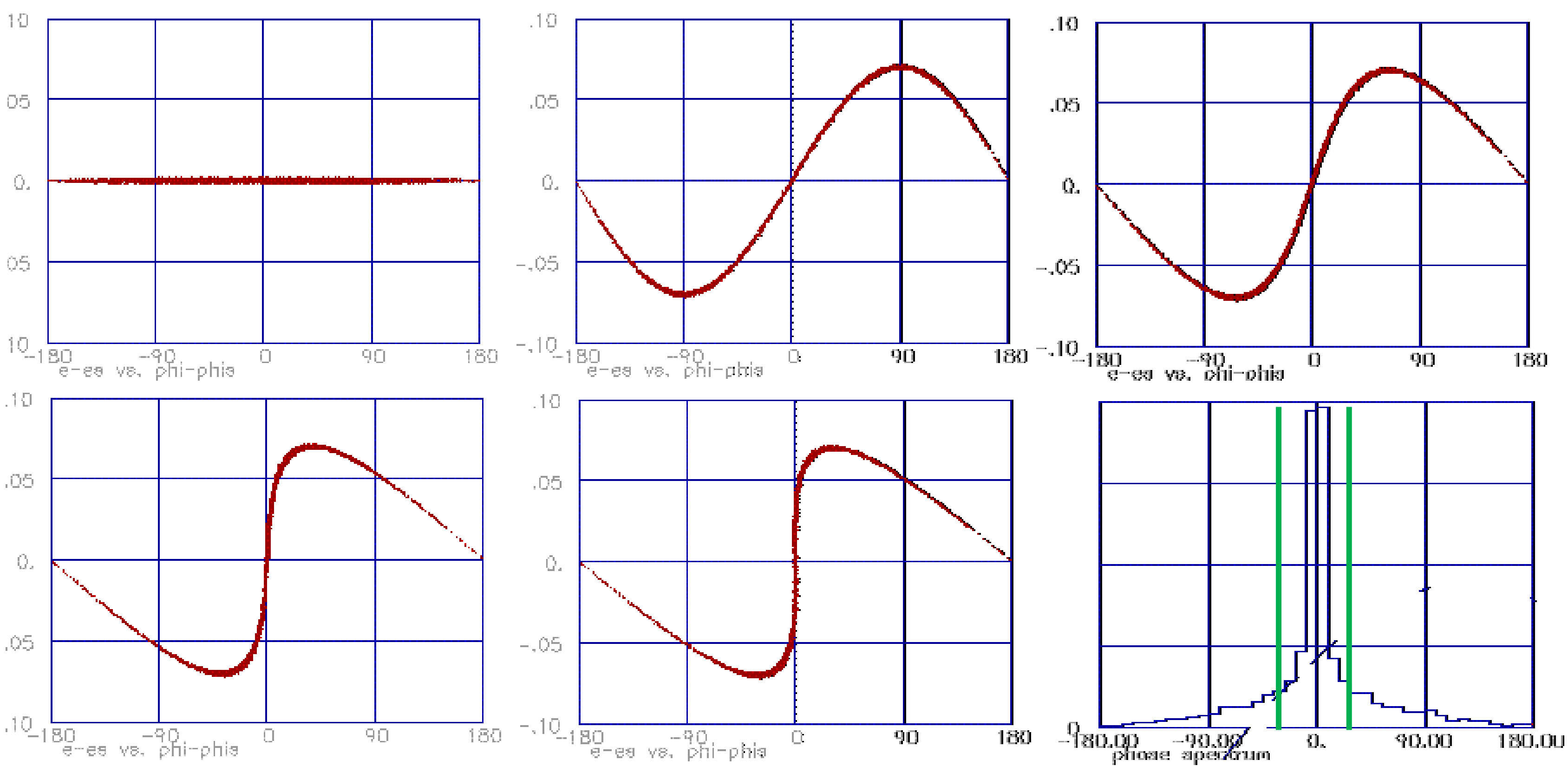
Separatrix



Longitudinal acceptance



Discrete Bunching

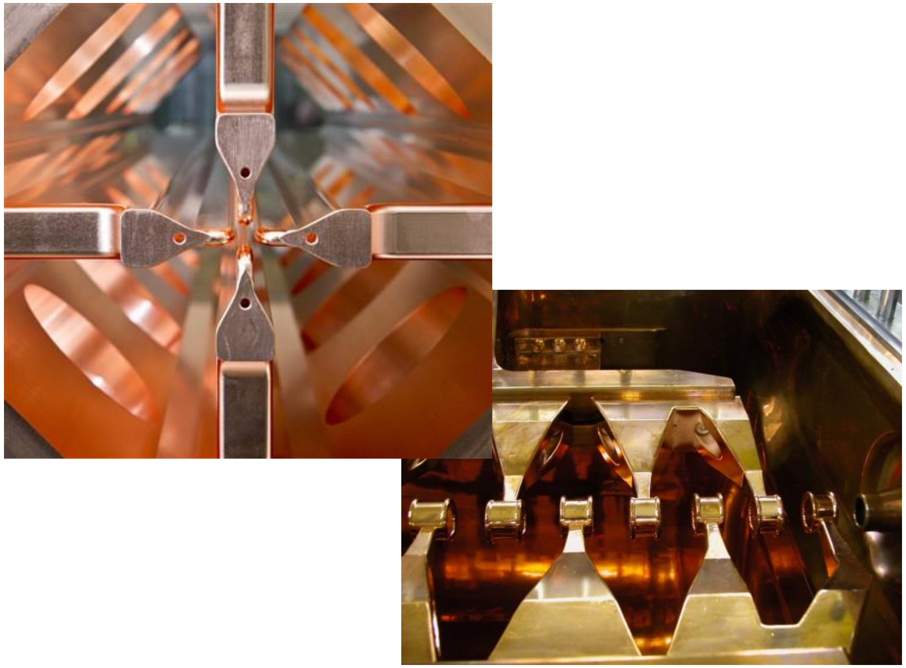


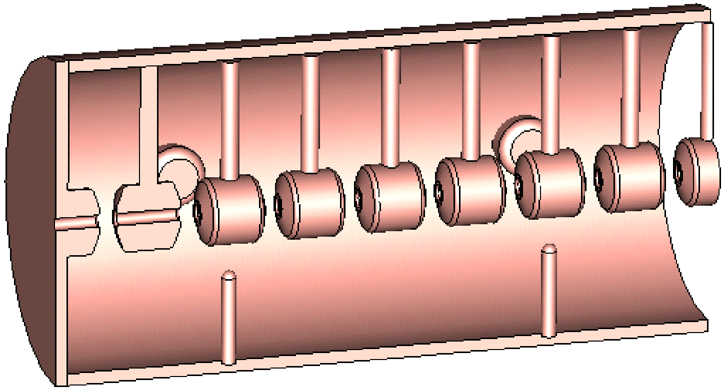
A rough bunching

Continuous beam	Interaction with RF	Energy distribution
Early part. are slowed down, late accelerated	After a drift	Final distribution of the particles

Basic accelerating structures for ions

- TE mode:
  - Radio Frequency Quadrupole: RFQ
  - Interdigital-H structure: IH
- TM mode:
  - Drift Tube Linac: DTL
  - Cavity Coupled DTL: CCDTL
  - PI Mode Structure: PIMS
  - Superconducting cavities





Medical electron Linacs

Medical electron Linacs

- By using higher frequencies, accelerators can be compacted. Here we provide two examples: one cavity of 11 GHz and another of 3 GHz.

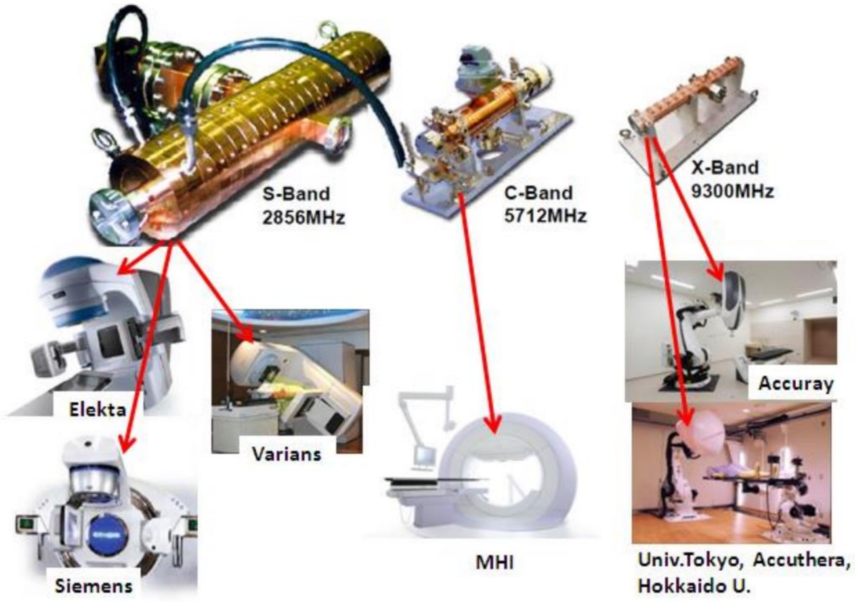
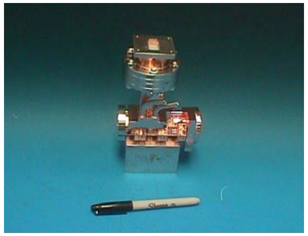


Figure 2. S-band (2.856GHz), C-band (5.712GHz), X-band (9.3GHz) accelerating structures and cancer therapy systems



11 GhZ
1 MeV

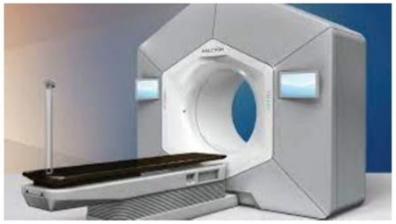
Medical electron Linacs

Compact Linacs

1. Siddarth II medical accelerator (INDIA)

2. uRT-506 Linac-CT| (CHINA)

3. Varian Halcyon 2.0 (USA)

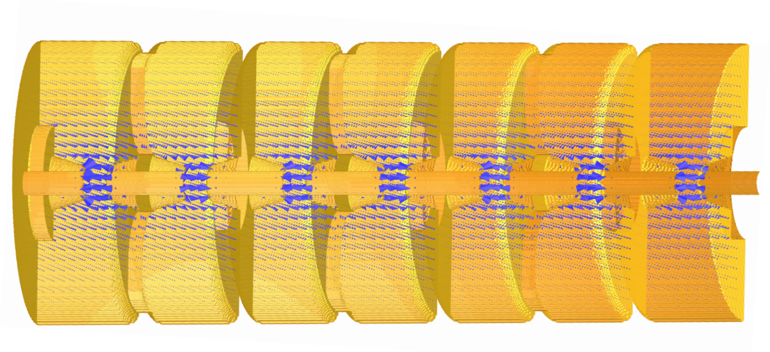


Comercial linacs now

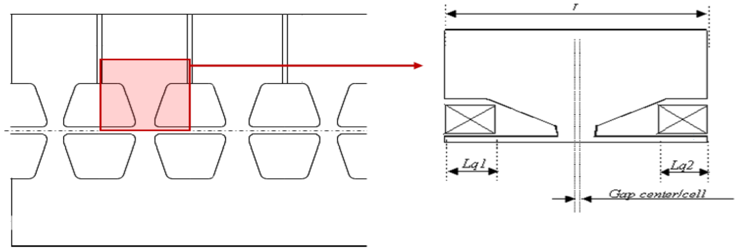
Designing an RF LINAC

- The cavities are used only once for each particle.
- So Linacs require high electric fields, and lots of cavities.

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



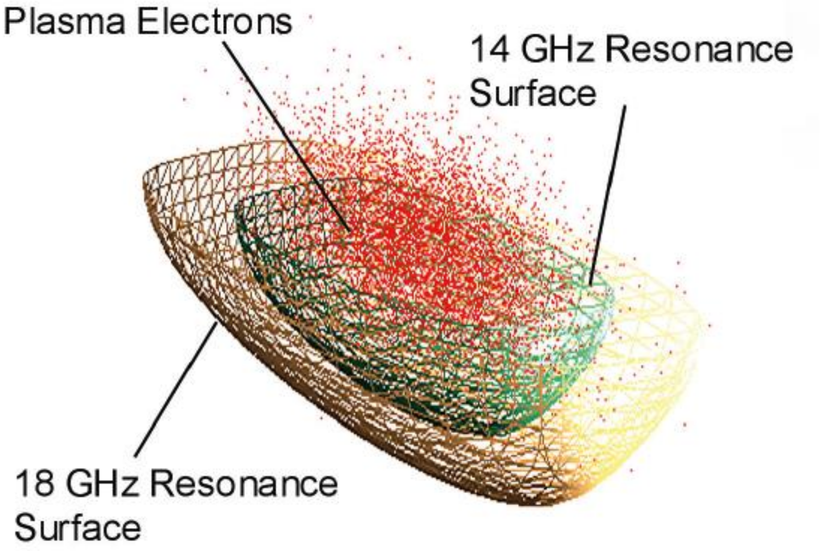
2. Beam dynamics design
   - Control the timing btw field and particles
   - Insure that the beam is kept in the smallest possible volume during acceleration

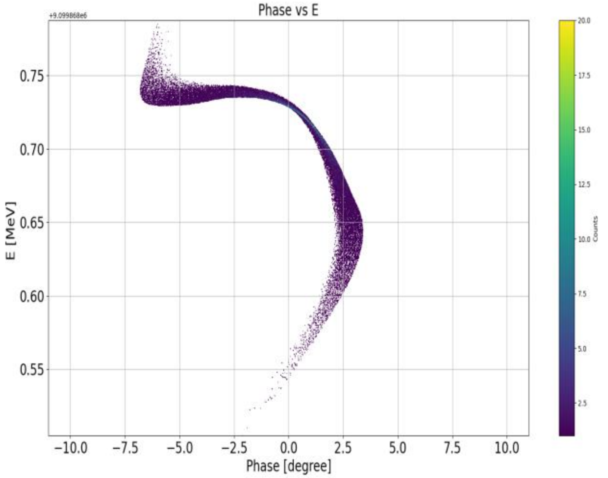


Designing an RF LINAC

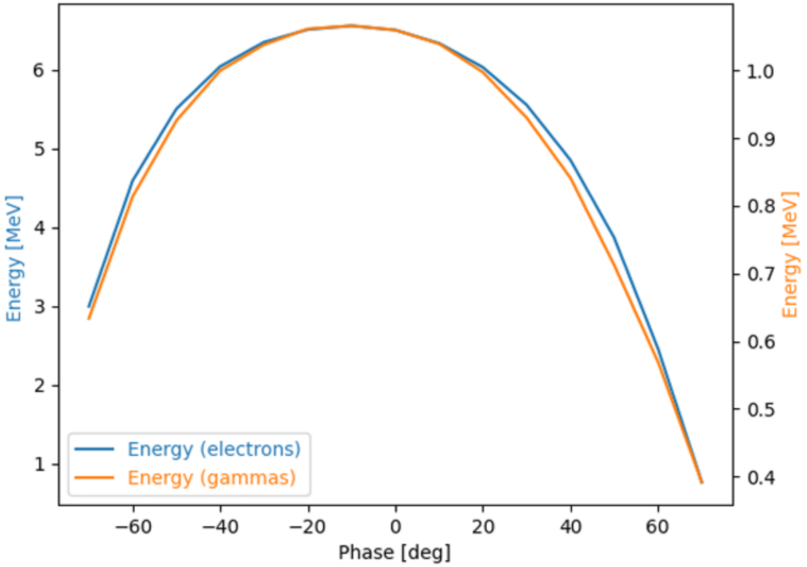
- **TOOLS:**

- GEANT4
  Beam matter interactions
- COMSOL, POISSON, CST
  Electromagnetic design
- GPT, TRAVEL,MADX, WARP
  Beam Dynamics
- CAD SOFTWARE
  Mechanical Design

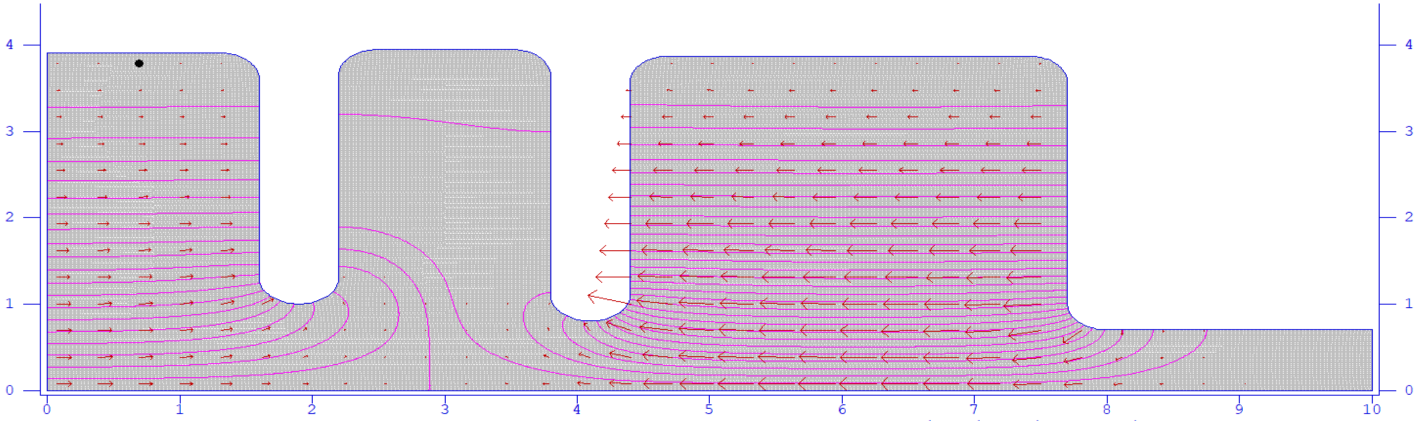


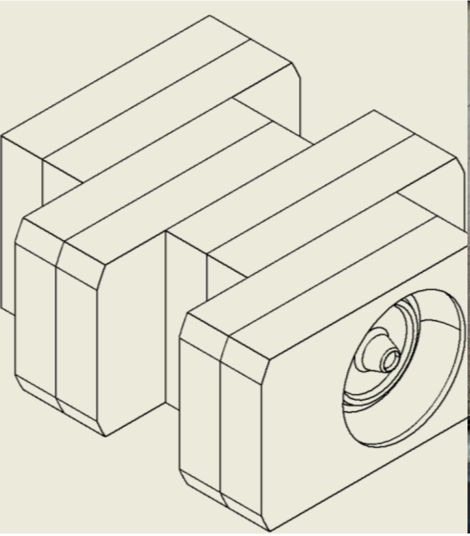


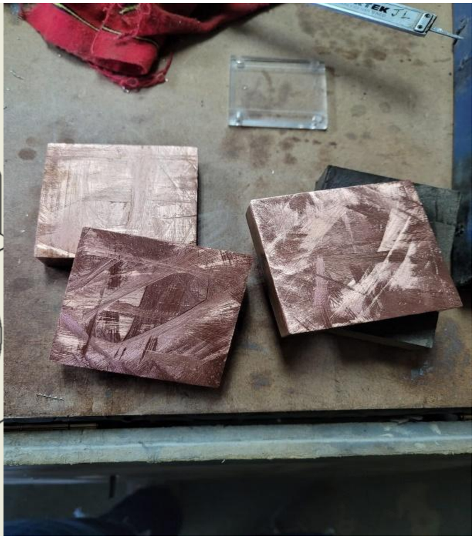
End-to-end simulation

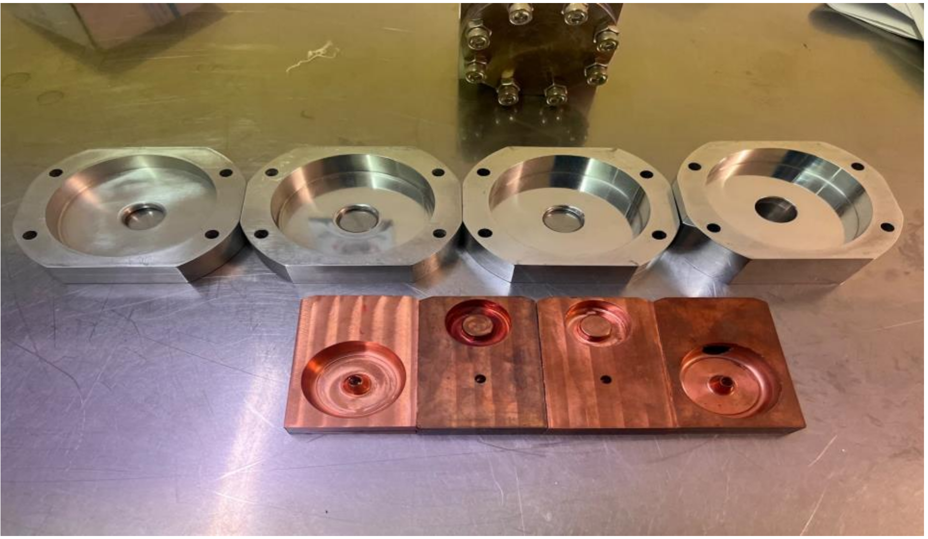


A end to end simulations has been made taking into account the way in how the particles temperature and space charge affect the beam formation and how the electrons interact with the Rf later collide with the target





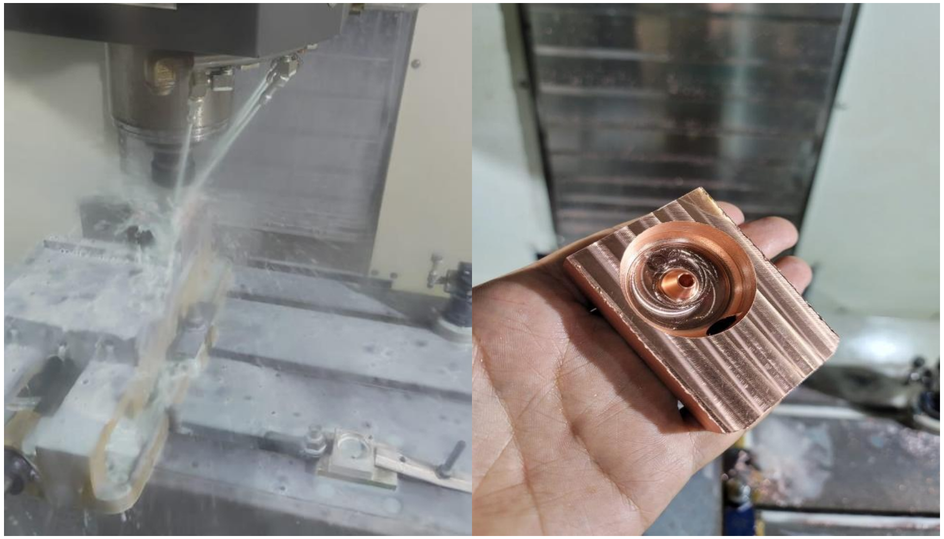




Radiofrequency cavity design in Mexico

- It is the heart of the linear accelerator and the most complicated part to design.
- The pieces were designed and machined in Mexico.
- There are two models of competitive cavities in the international field with publications about them.

Error in resonance within 0.1%



Radiofrequency cavity design in Mexico

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Breast cancer in Mexico: challenges and barriers

- **High mortality rates**

Due to limited access to advanced and timely treatments.

- **Cultural and socioeconomic barriers**

Among indigenous women, there are barriers to early detection due to a lack of knowledge and the stigma associated with cancer.

- **Inequalities in the quality of care**

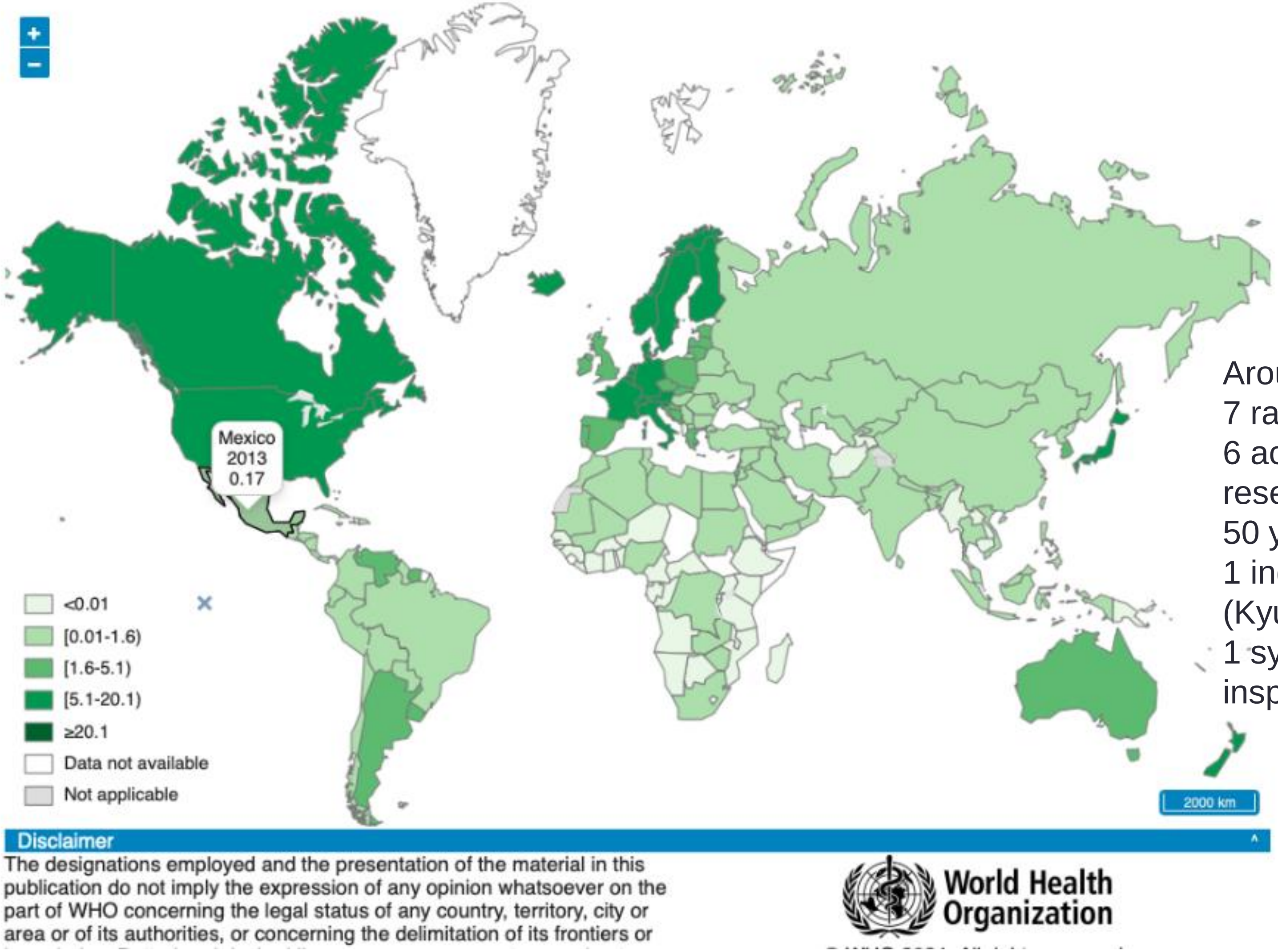
Economic difficulties limit access to quality health services.

- **Limitations in access to health services**

Economic and social difficulties prevent many women from receiving adequate care.

- **Importance of addressing these challenges**
- Reducing these barriers is crucial to decreasing mortality rates from breast cancer in Mexico.
  https://bmccancer.biomedcentral.com/articles/10.1186/1471-2407-14-658

Accelerators in Mexico



Disclaimer

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of WHO concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or

Around 70 medical Linacs.
7 radiopharmacies.
6 accelerators for scientific research (some with more tha
50 years of use).
1 industrial irradiator (Kyunshing of Mexico)
1 system of Linacs for cargo inspection.

Challenges

Vacuum

Radio frequency

High voltage

Reliability

Magnet design

Gas injection

Complicate Designs

Beam losses

Instrumentations

Space charge

Secondary Electrons

Users always want more

Gracias !!