Outline: Linac-Synchrotron

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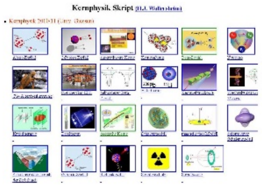
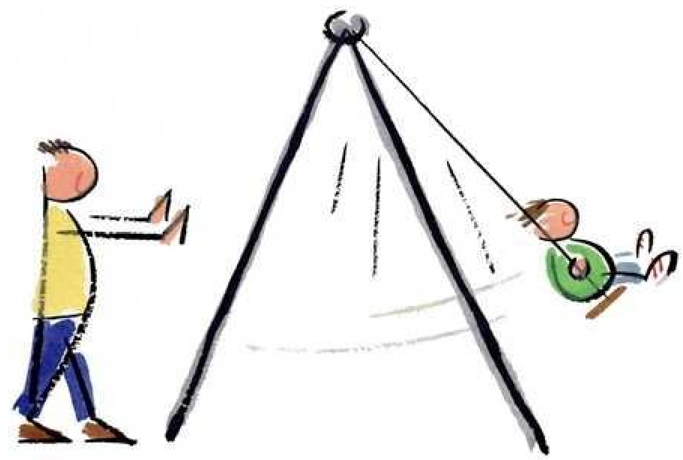


1. linear and circular accelerator
2. Wideroe structure
3. Alvarez structure
4. Linac and synchrotron
5. synchrotron: beam extraction

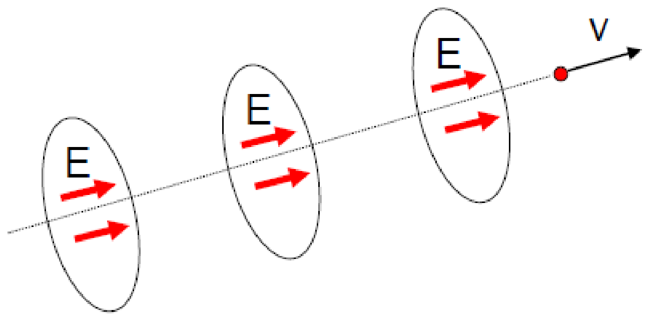
Acceleration to higher energies

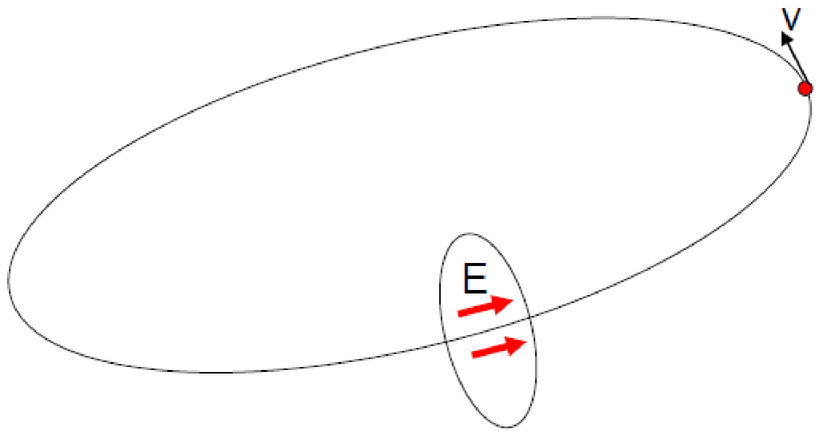
- While terminal voltages of 20 MV provide sufficient beam energy for nuclear structure research, most applications nowadays require beam energies > 1 GeV
- How do we attain higher beam energies?
- Analogy: How to swing a child?
  - Pull up to maximum height and let go: difficult and tiring (electrostatic accelerator)
  - Repeatedly push in synchronism with the period of the motion



Acceleration by repeated application of time-varying fields

- Two approaches for accelerating with time-varying fields
- Make an electric field along the direction of particle motion with Radio-Frequency (RF) cavities





Linear Accelerators

Use many accelerating cavities through which the particle beam passes once.

Circular Accelerators

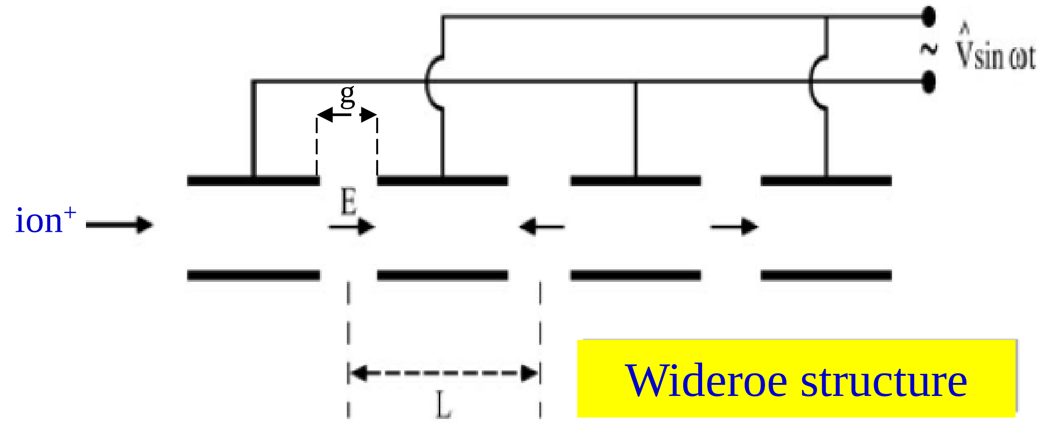
Use one or a small number of RF accelerating cavities and make use of repeated passage through them: This approach leads to circular accelerators:

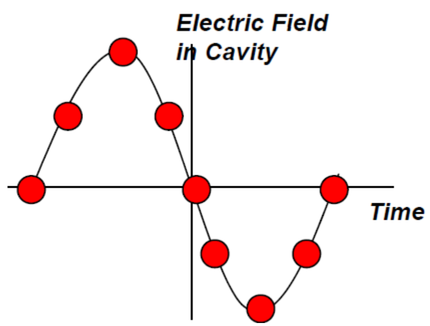
Cyclotrons, synchrotrons and their variants.

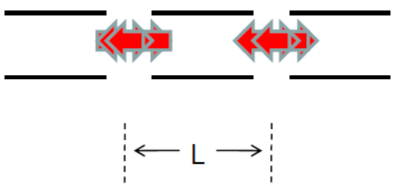
- The electric field is no longer static but sinusoidal alternating half periods of acceleration and deceleration.

$$V(t) = V_0 \cdot \sin \omega t$$

$$E(t) = (V_0/g) \cdot \sin \omega t$$



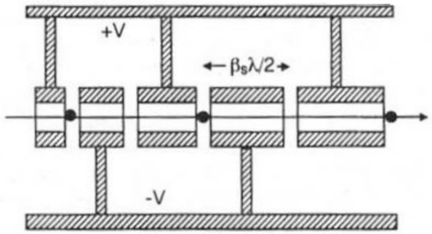




Rolf Wideroe (1902-1996)

- Three important aspects of an RF linear accelerator
  - Particles must arrive bunched in time in order for efficient acceleration
  - Acceleration gaps must be spaced, so that the particle “bunches” arrive at the acceleration phase:

$$L = v \cdot \frac{T}{2} = \beta c \frac{1}{2}\frac{\lambda}{c} = \beta \frac{\lambda}{2}$$



  - The acceleration field is varying while the particle is in the gap; energy gain is more complicated than in the static case.

Acceleration in the Wideroe structure

Energy gained after ***n*** acceleration gaps:

$$E_n = n \cdot q \cdot U_0 \cdot \sin \Psi_s$$

n	number of gaps between the drift tubes
q	charge of the particles
U_0	peak voltage of the RF system
Ψ_s	synchronous phase of the particles

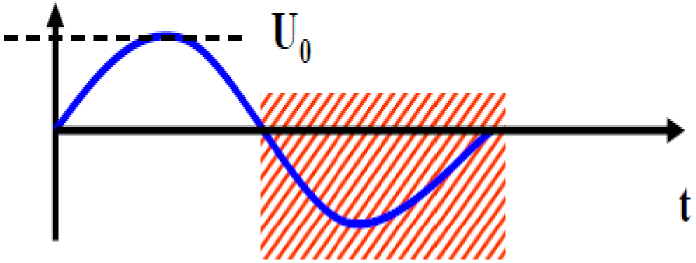
Kinetic energy of the particles:

$$E_n = \frac{1}{2} m \cdot v_n{}^2$$ (valid for non-relativistic particles)

Velocity of the particles:

$$v_n = \sqrt{\frac{2E_n}{m}} = \sqrt{\frac{2 \cdot n \cdot q \cdot U_0 \cdot \sin \Psi_s}{m}}$$

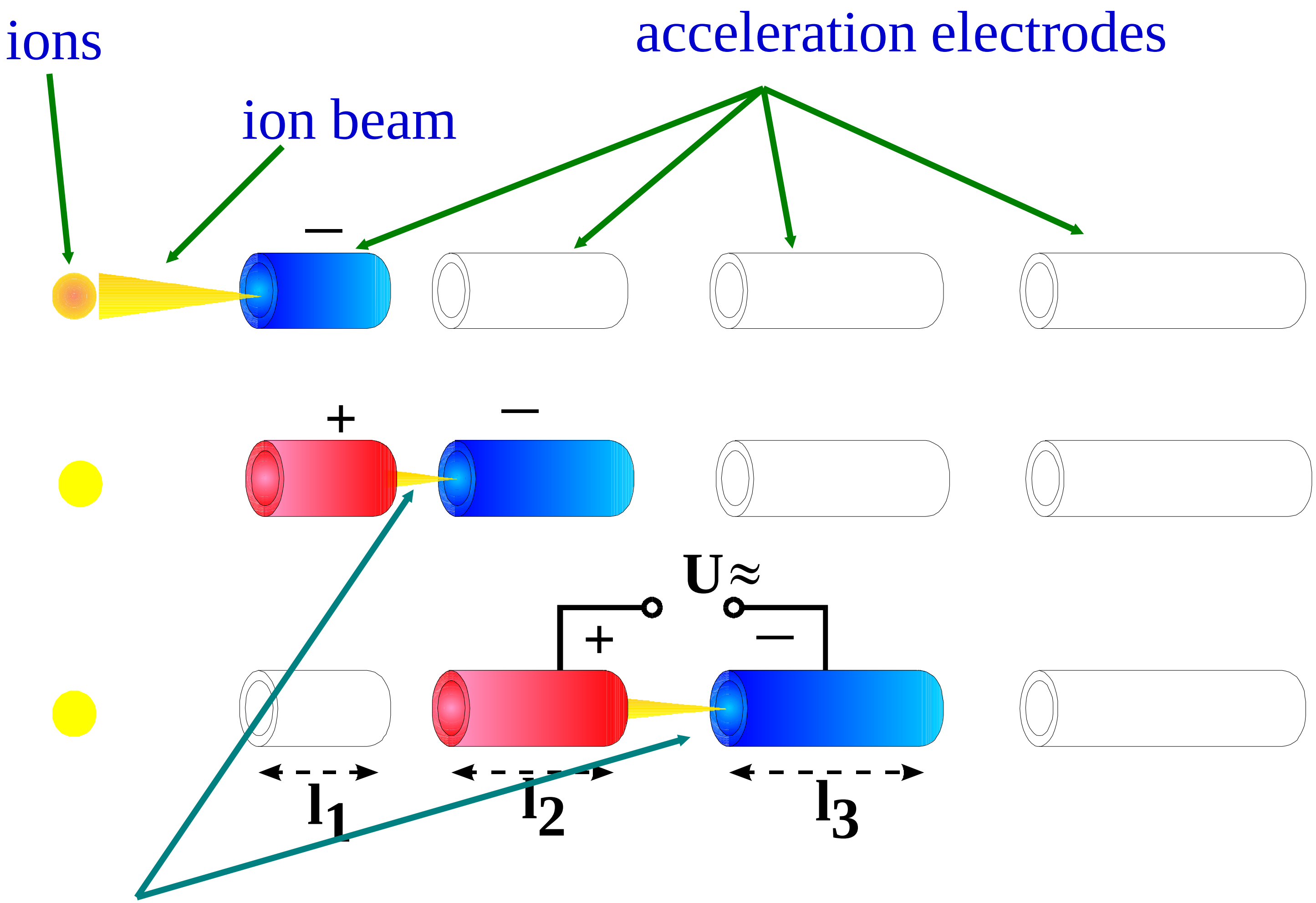
Shielding of the particles during the negative half wave of the RF



Length of the n-th drift tube:

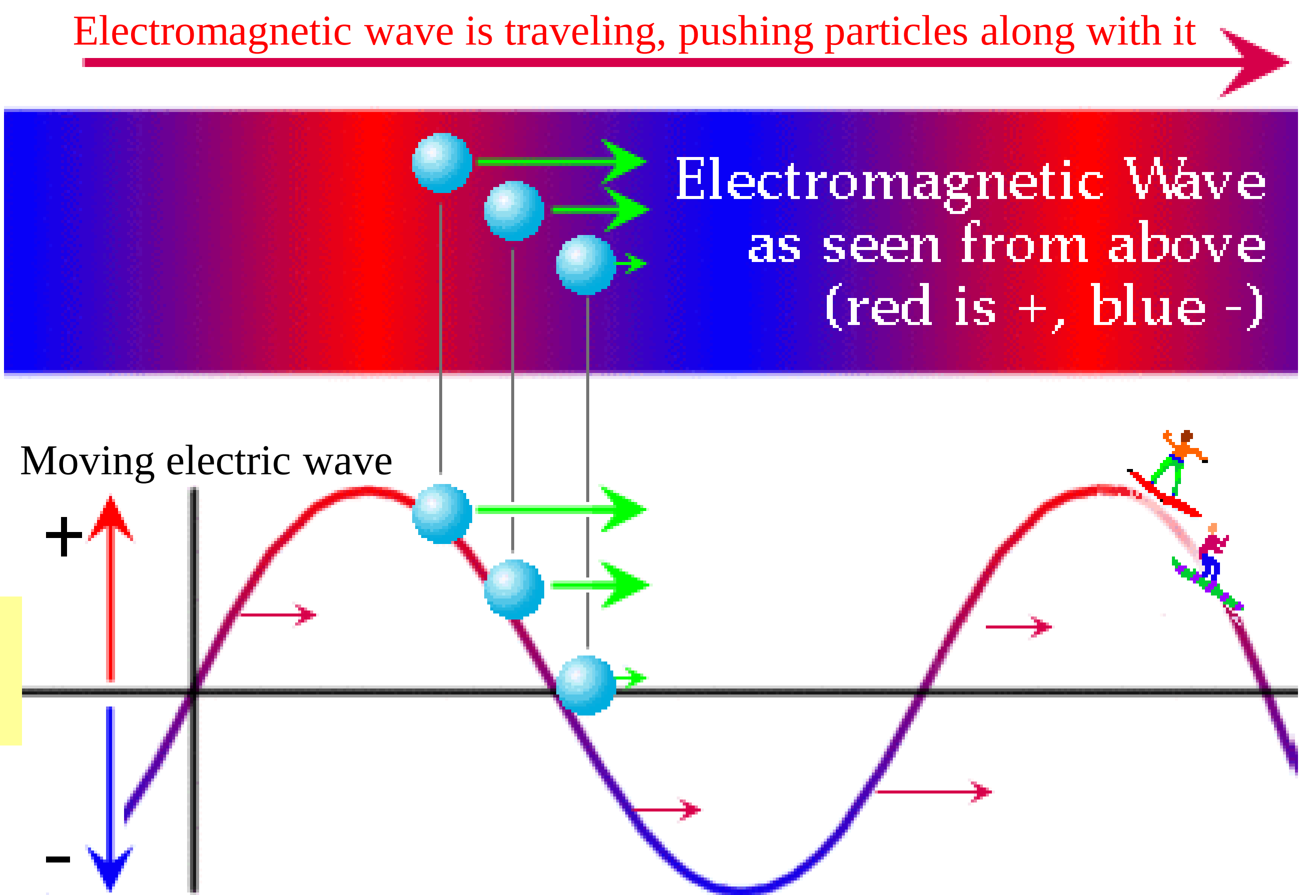
$$l_n = v_n \cdot \frac{\tau_{RF}}{2} = v_n \cdot \frac{1}{2 \cdot \nu_{RF}}$$

Linear accelerator



acceleration only between the electrodes

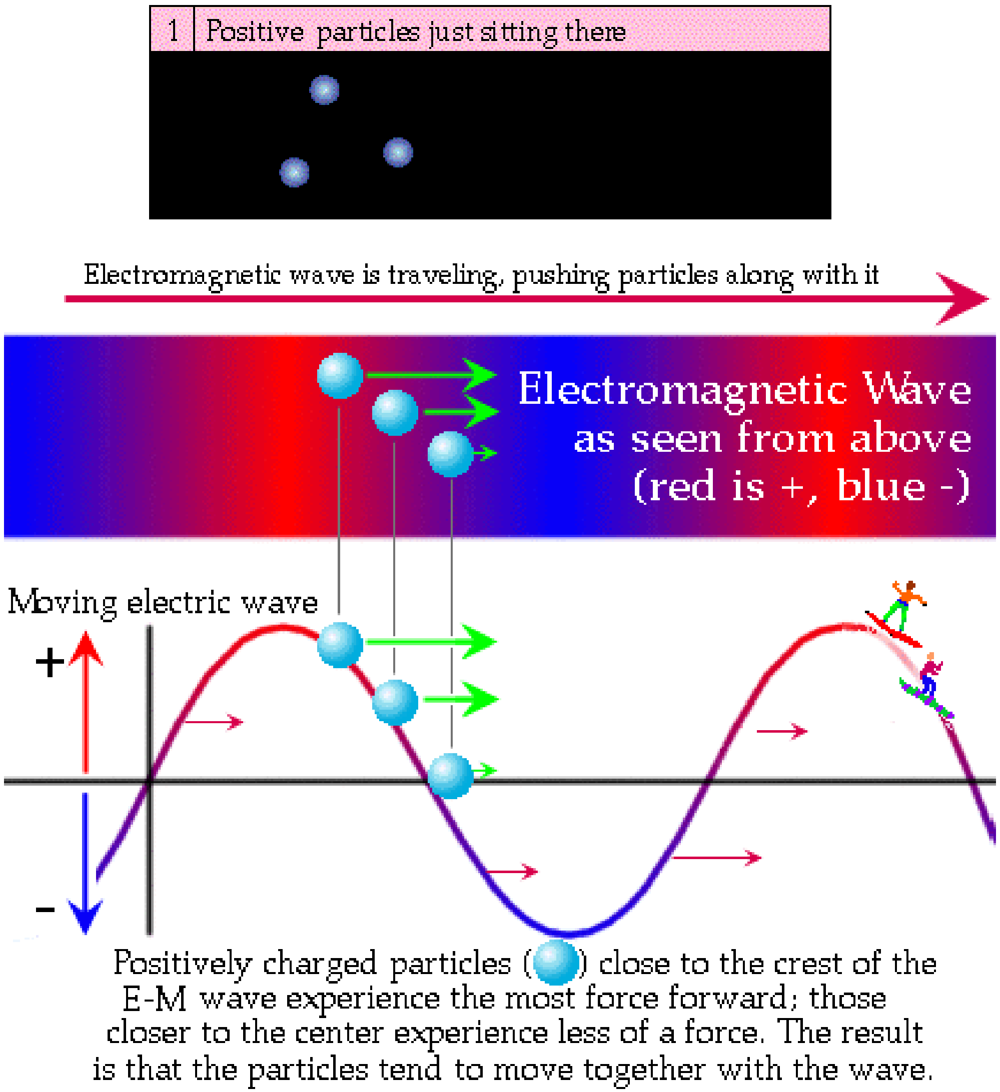
Principle of the acceleration



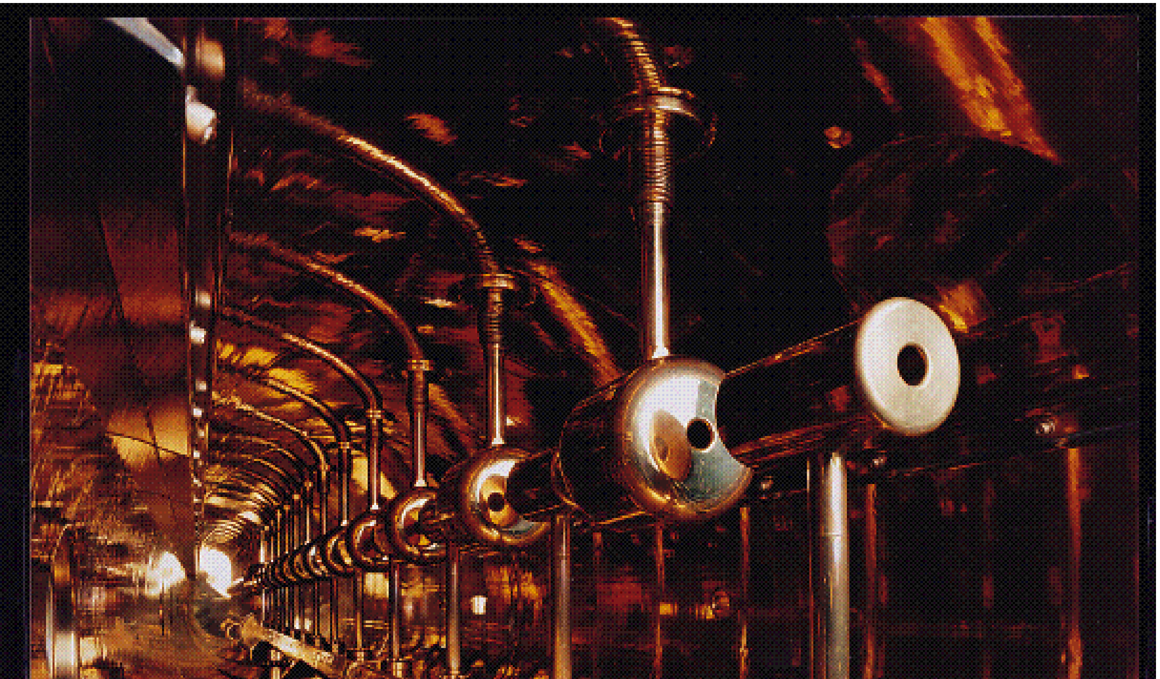
RF in phase with particles

Positively charged particles ( ) close to the crest of the E-M wave experience the most force forward; those closer to the centre experience less of a force. The result is that the particles tend to move together with the wave.

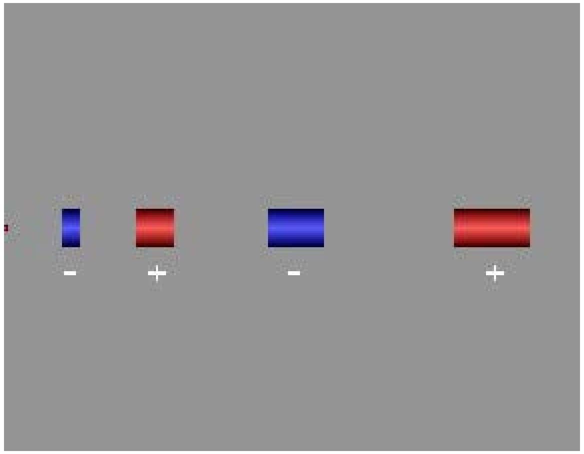
Principle of the acceleration



Wideroe structure at GSI

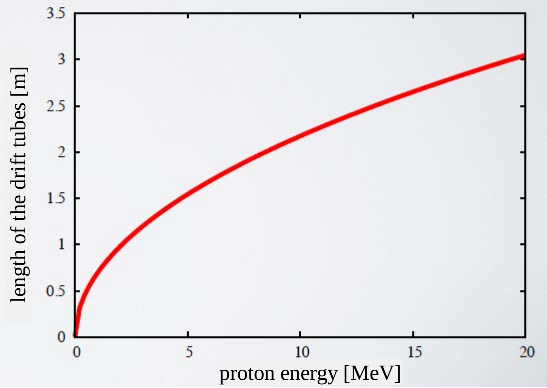


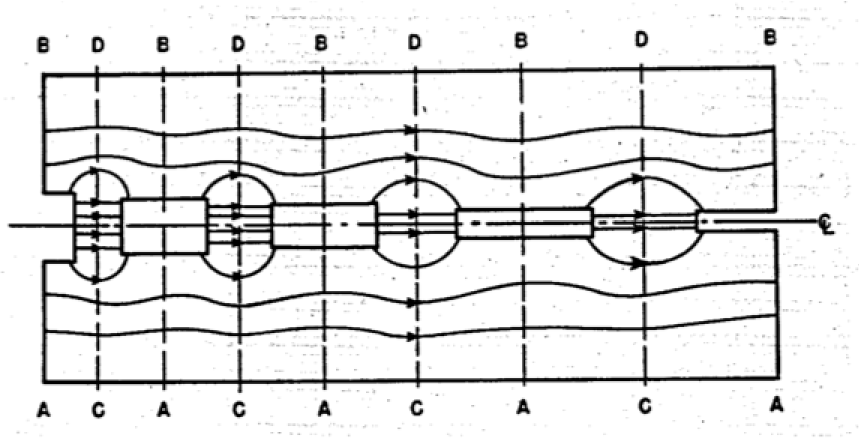
27 MHz Radio frequency



Alvarez structure – standing-wave linear accelerator

- The Wideroe linac is only efficient for low-energy heavy ions
- When using 10 MHz frequency, the length of the drift tubes would act more like antennas and becomes prohibitive for high-energy protons





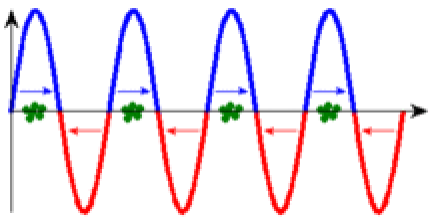
Luis W. Alvarez
(1911-1988)

- **Alvarez accelerator = resonant cavity**

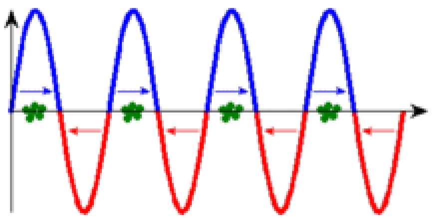
  Standing waves with E-field along direction of particle motion. While the electric fields point in the "wrong direction" the particles are shielded by the drift tubes.

  The accelerator consists of a long "tank" (radius determines frequency). Drift tubes are placed along the beam axis, so that the accelerating gaps satisfy synchronicity condition with drift tube length L given by $L = \beta\lambda_0$ where λ_0 is the free space wavelength at the operating frequency.

Principal of an accelerated particle package



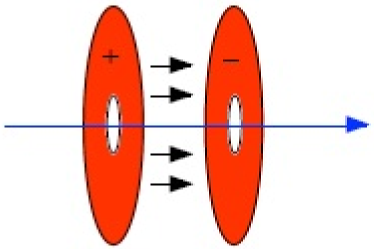
moving wave



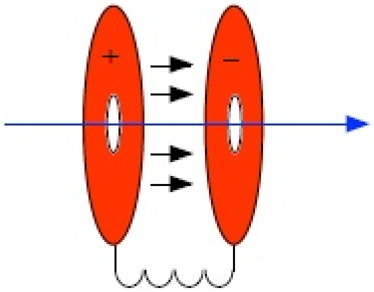
standing wave

RF Cavity

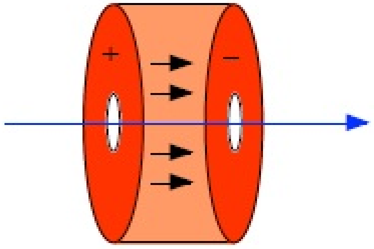
A parallel plate capacitor has an E-field inside, which can accelerate particles. Putting holes in the plates doesn't change the field much.



Connecting the plates by an inductor makes a resonant circuit with $\omega^2 = {}^{1}/_{L \cdot C}$

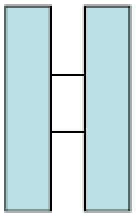


Putting many inductors in parallel around the edges of the plates just lowers the inductance and raises the frequency. In fact, you can connect the plates with a metal cylinder!



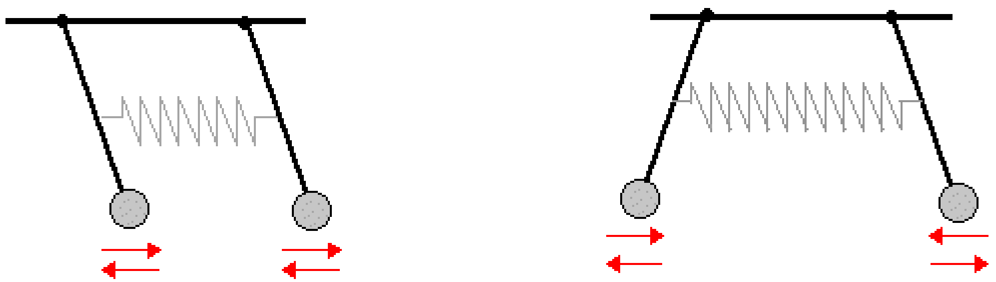
Coupling of two cavities

❖ Suppose we couple two RF cavities together:
- Each is an electrical oscillator with the same resonant frequency
- A beampipe couples the two cavities



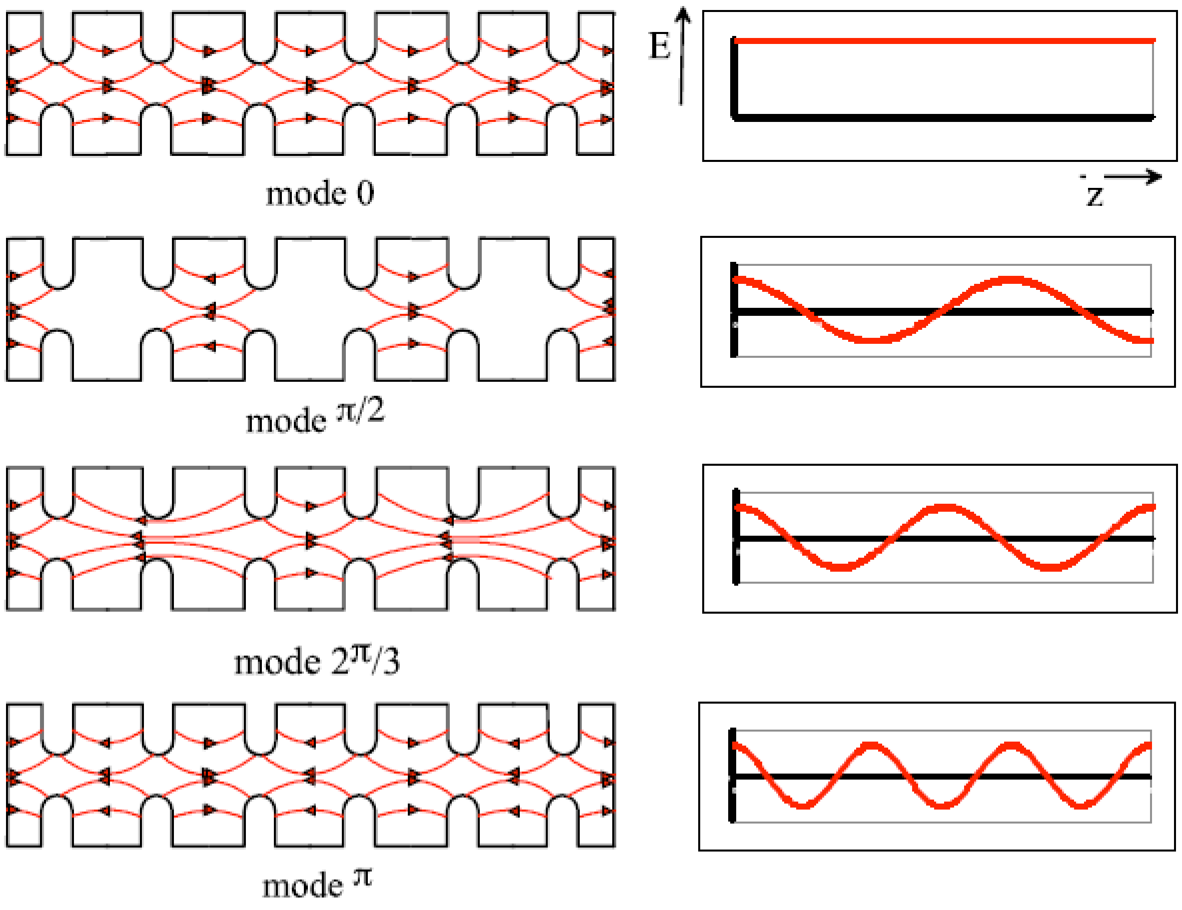
❖ Remember the case of mechanical coupling of two oscillators:

❖ Two mechanical modes are possible:
- The "zero-mode": $\phi_A - \phi_B = 0$, where each oscillates at natural frequency
- The "pi-mode": $\phi_A - \phi_B = \pi$, where each oscillates at a higher frequency



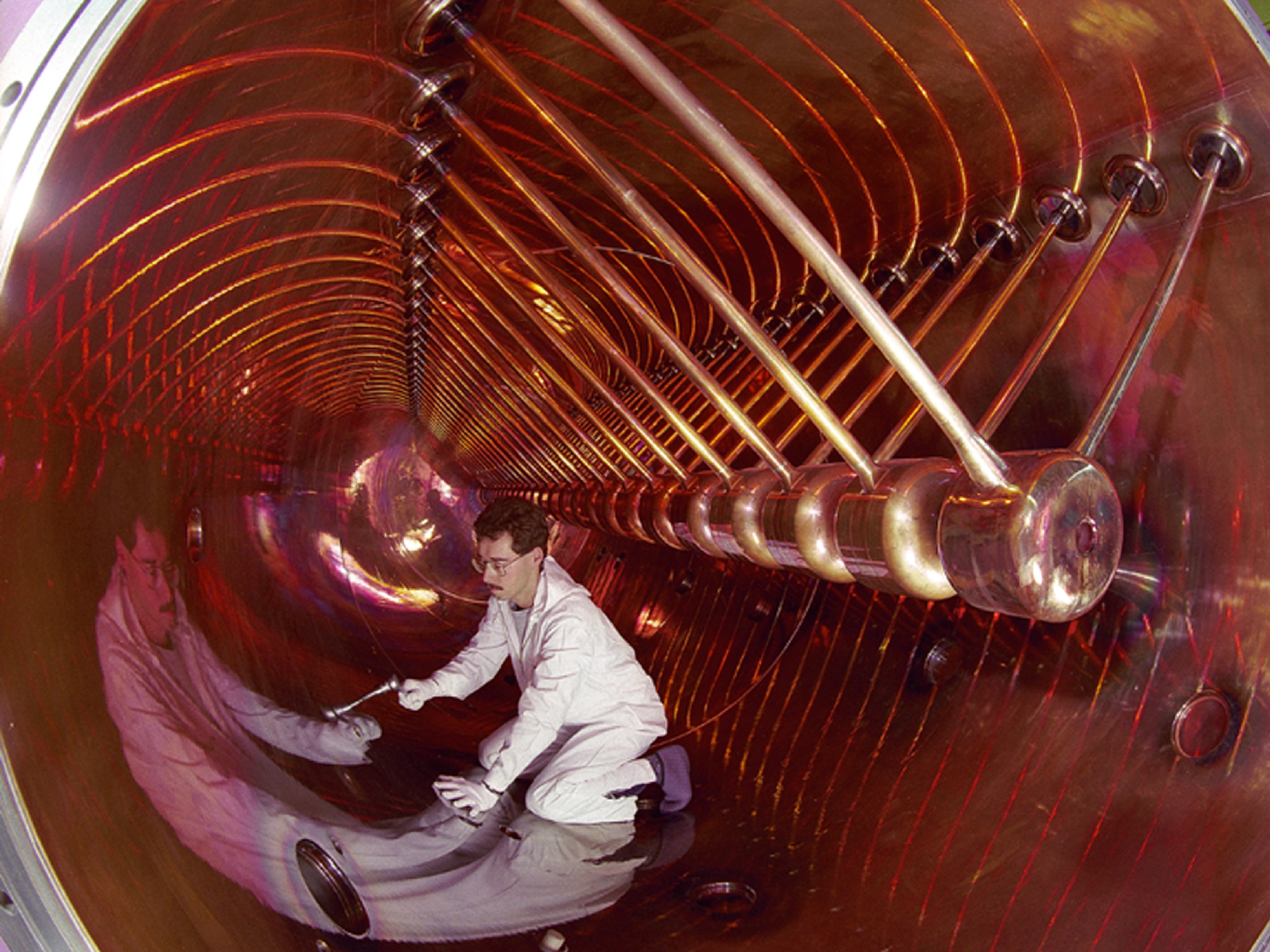
❖ Standing wave structures of coupled cavities are all driven so that the beam sees either the ***zero*** or $\boldsymbol{\pi}$ mode.

Standing wave cavities

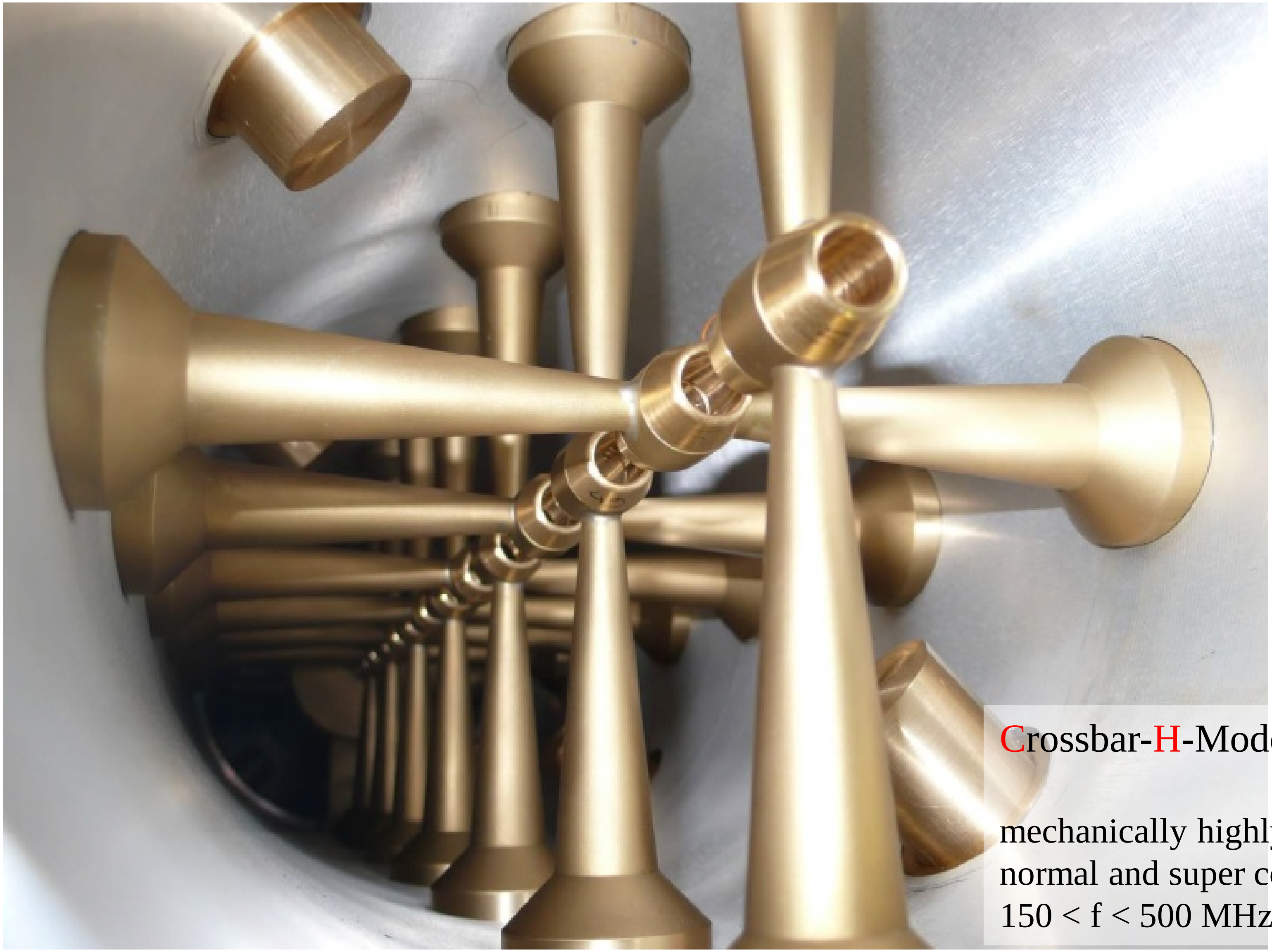


The mode names correspond to the phase difference from one cell to the next

UNILAC Alvarez Accelerator



CH-cavity for FAIR p-Linac

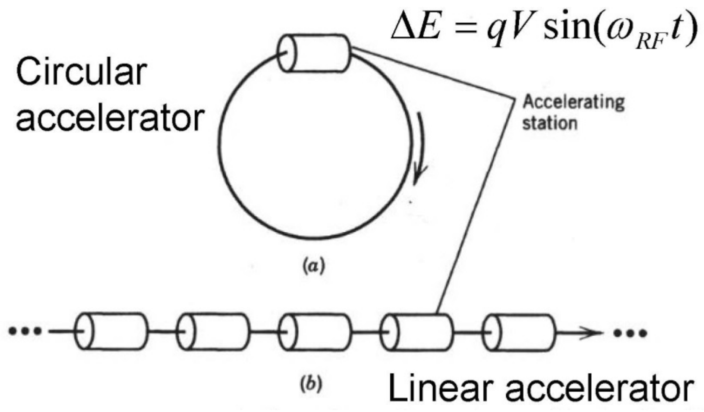


Crossbar-H-Mode-Cavity

mechanically highly stable
normal and super conducting
150 < f < 500 MHz

Synchrotron

As linacs are dominated by cavities, circular machines are dominated by magnets



- Both the accelerating field frequency and the magnetic field strength change synchronously with time to match energy and keep revolution radius constant.
- Magnetic field produced by several bending magnets increases with momentum. For high energy:

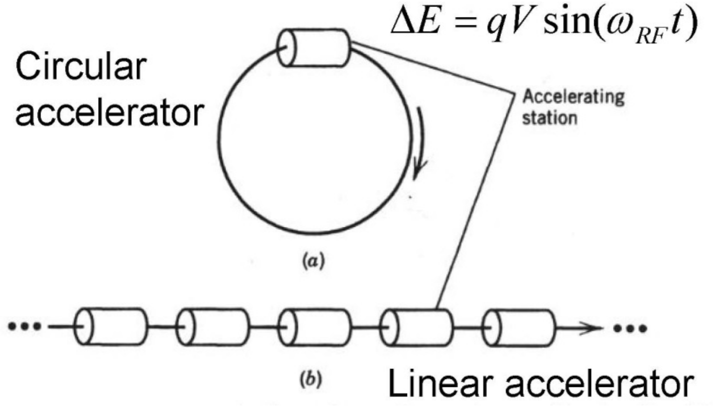
$$E_{proton}[GeV] \approx 0.3 \cdot B\rho[T \cdot m]$$

- Practical limitations for magnetic field → high energies only at large radius.

example: 100 GeV protons

- Fe-magnet B ~ 1.5 T → R = 222 m
- superconductive magnet B ~ 5 T → R = 67 m

Synchrotron



Mark Oliphant
(1901-2000)

- The bending field changes with particle beam energy to maintain a constant radius:

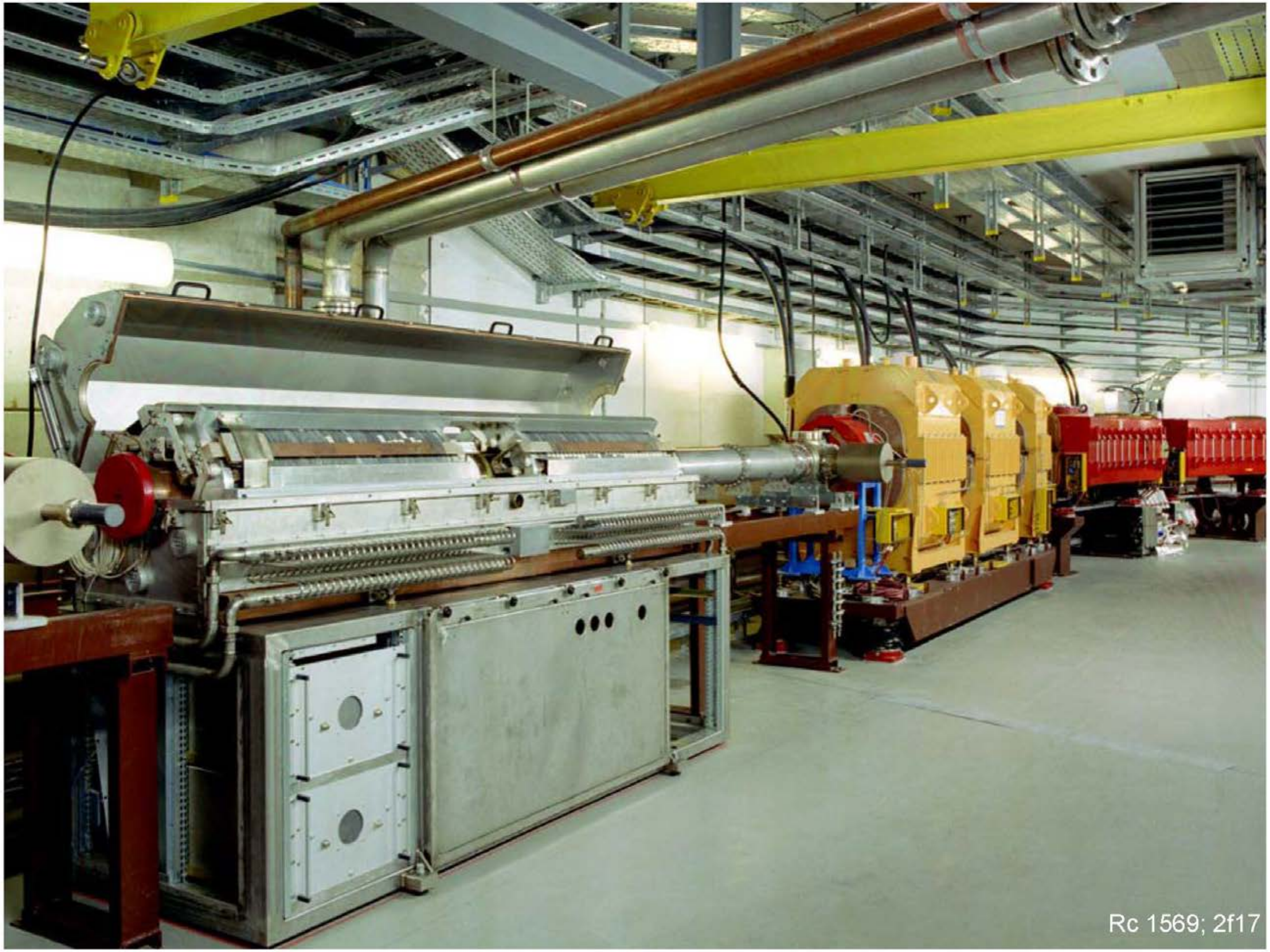
$$\frac{1}{\rho[m]} = 0.3\,\frac{B[T]}{\beta E[GeV]} = 0.3\,\frac{B[T]}{cp[GeV]}$$

- So ***B*** ramps in proportion to the momentum. The revolution frequency also changes with momentum.
- The synchronicity condition, including now the relativistic term, is

$$\omega = \frac{qB}{m\gamma}$$

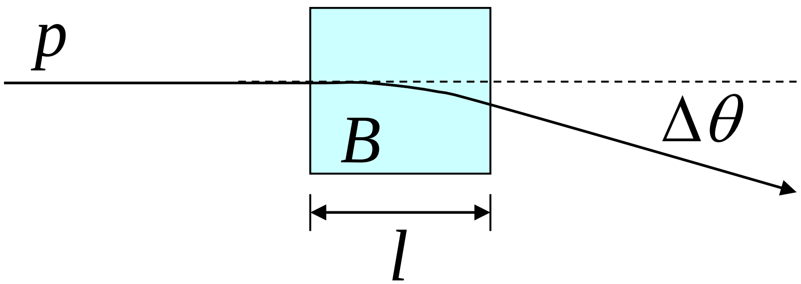
- For an electron synchrotron, the injected beam is already relativistic, so only the magnetic field changes with beam energy.
- For a proton synchrotron, the injected beam is not yet relativistic, so the RF accelerating frequency and the magnetic field both ramp with energy.

SIS - SchwerIonenSynchrotron



Thin lens approximation and magnetic "kick"

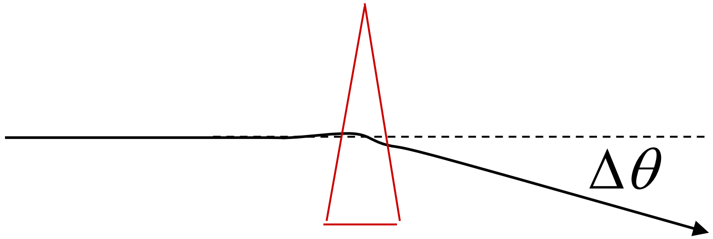
- If the path length through a transverse magnetic field is short compared to the bend radius of the particle, then we can think of the particle receiving a transverse "kick", which is proportional to the integrated field



$$\boxed{p_\perp \approx qvBt = qvB(l/v) = qBl}$$

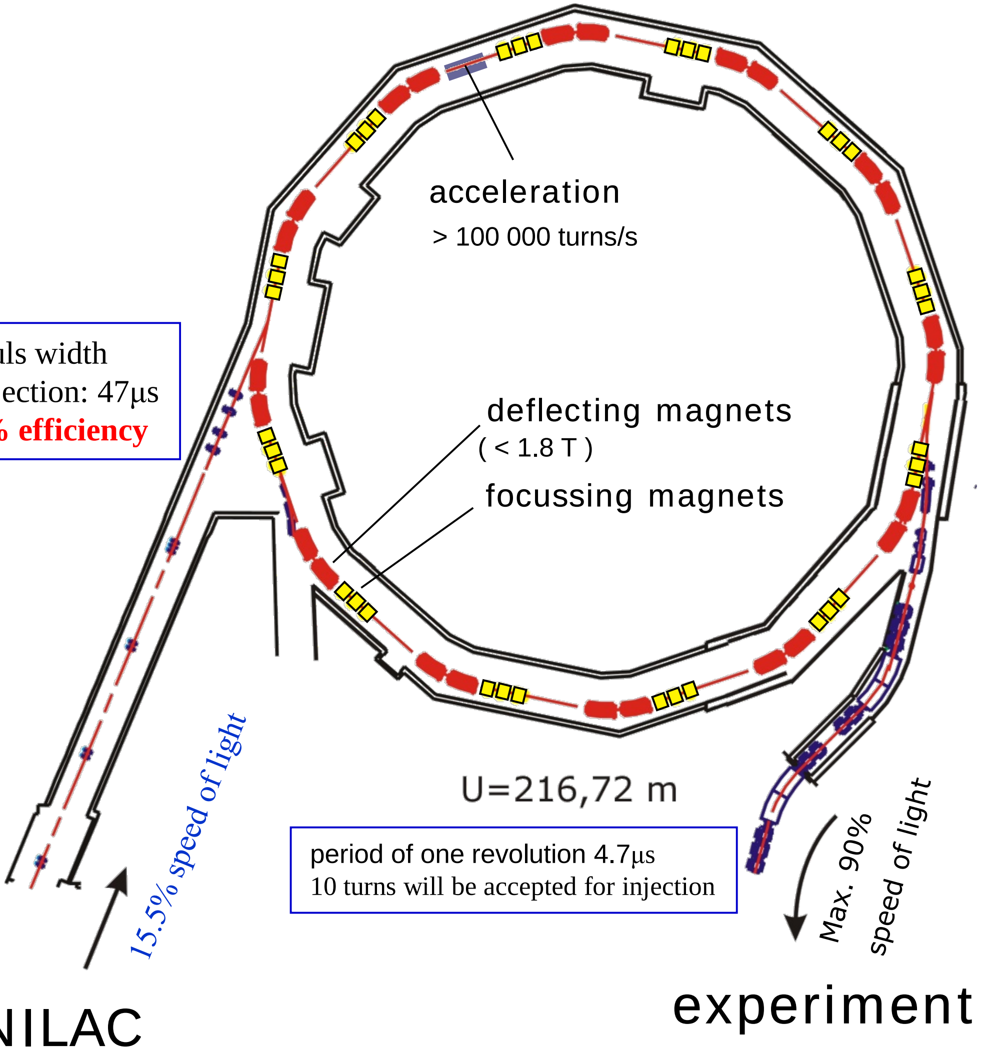
and it will be bent through small angle

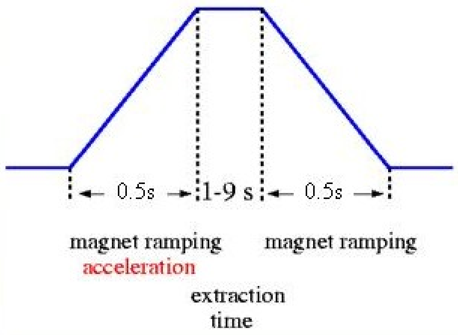
$$\boxed{\Delta\theta \approx \frac{p_\perp}{p} = \frac{Bl}{(B\rho)}}$$

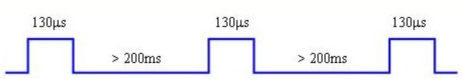


SIS - SchwerIonenSynchrotron

eff. puls width
for injection: 47µs
36.2% efficiency







Ion	Number of injections	Intensity [spill^{-1}] at FRS	Ion source	Date
^{58}Ni	1	$6*10^9$	MEVVA	3.2006
^{107}Ag	1	$3*10^9$	MEVVA	2.2006
^{124}Xe	1	$5*10^9$	MUCIS	3.2008
^{136}Xe	4	$5*10^9$	MEVVA	7.2006
^{208}Pb	30	$1.3*10^9$	PIG	3.2006
^{238}U	1	$2.0*10^9$	PIG	9.2009

intensity[s^{-1}]=0.5*intensity[spill^{-1}]