L2. Accelerator types

① Electrostatic acceleration

$\vec{F} = \dot{\vec{p}} = q\vec{E} \qquad \vec{E} = -\vec{\nabla} V$

electrons $m_e = 0{,}511$ MeV

$E = 2$ MeV

$\beta = 0{,}979$ relativistic

→ How to produce large potentials?

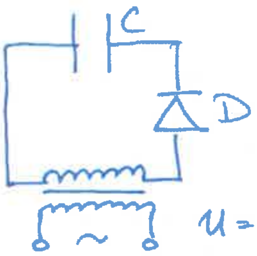
– (1932) Cockroft & Walton - generator → cascade amplifier → $V \sim$ a few 100 kV
1921 Greinacher

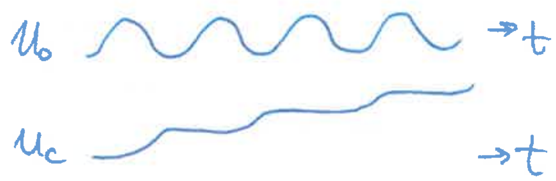
Accelerator physics books in English

An Introduction to beam physics
Martin Berz et al
CRC Press 2015
ISBN: 978 1 4200 1182 1

Particle Accelerator Physics
Helmut Wiedemann
Springer 2007
ISBN: 978 3 540 49045 6

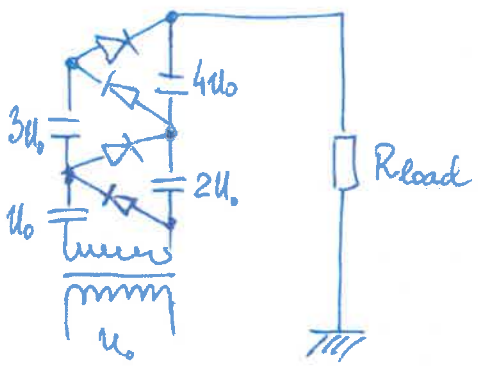
– element





after some loadings $U_c = U_0$

„Gleichrichter" – AC → DC converter



total voltage

$U = 2nU_0 - \Delta U \pm \delta U$

↑ number of cascade stages

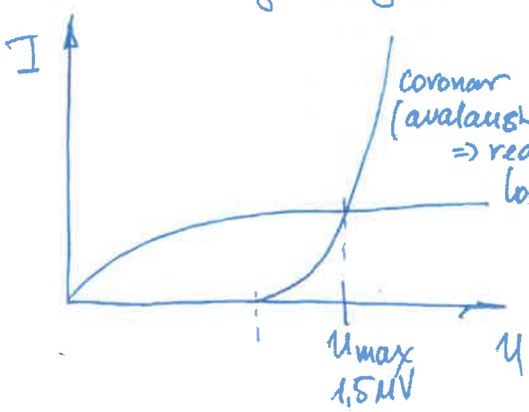
slide

ΔU – voltage drop due to loading (accelerated particles ⇒ current)

$$\Delta U = \frac{I}{fC}\left(\frac{2}{3}n^3 + \frac{1}{4}n^2 + \frac{1}{12}n\right)$$

U_0 frequency 0,5 – 10 kHz; capacitance 1 – 10 nF; n: 3-5, cannot be very large

– Current-Voltage diagram



$|E| = U/r_0$

– maximum E on polished stainless steel in UHV ~ 100 kV/cm

for higher E, emission of e^- from surface

today | injectors, Medicine & Technology as
ⓝ source $d\,(200\text{-}800\text{ keV}) + t = \alpha + n\ (14.1\text{ MeV})$

- Higher voltages

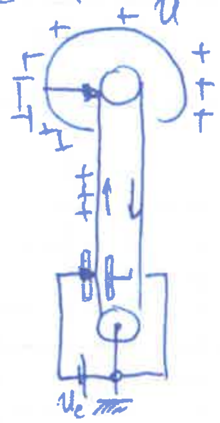
  SF_6 - sulfur hexafluorid 89 kV/cm (dielectric strength)
  $80\,N_2 + 20\%\,CO_2$ nitrogen + carbon dioxide
  @ high pressure e.g. 20bar

- Other electrostatic accelerators

  - Dynamitron® (IBA) 1960s
    $\nu = 30-300$ kHz $I \simeq 10$ mA $n \gg n_{sc}$ $U = 2 n f_c U_0$
  - Marx Generator Erwin Otto Marx 1923
    idea : - a chain of capacitors in parallel (loading)
    - connection them in series by spares →
    ⇒ ignition of a short HV pulse

    (slide)

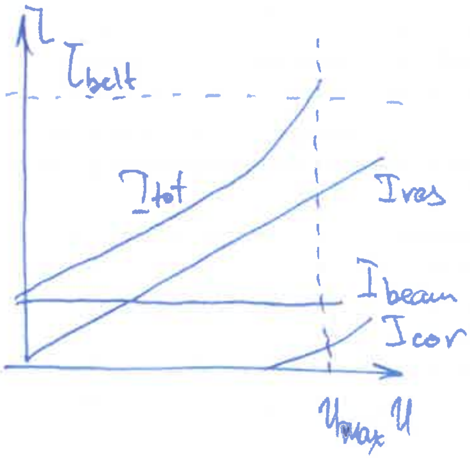
- Van de Graaf Belt Generator
  - idea: charge "electromechanically" condensator
    $U = Q/C$ require large Q for large U
  - spere as C - $C = 4\pi\varepsilon\varepsilon_0 r$
    $r = 1m$, $C = 111\,pF$



  - use belt to charge the sphere
    pellets → pelletron
    ladders → laddertron

$$\frac{dU}{dt} = \frac{1}{C}\frac{dQ}{dt} = \frac{1}{C}\left(I_{belt} - I_{beam} - I_{res} - I_{cor}\right)$$

belt, beam, resistivity of the chain, coronal discharge
losses which limit U_{max}

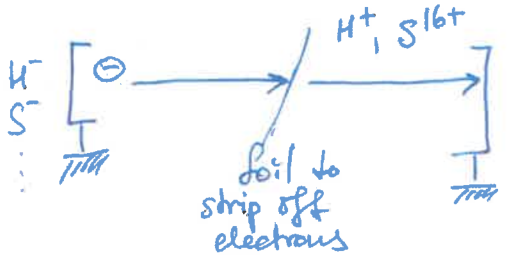


$U_{max} \sim 10$ MV up to ~15 MV
MPIK ~ 25 MV

$$\frac{\Delta E}{E}(\text{beam}) \sim 10^{-4}$$

(slide)

- tandem accelerator (Van de Graaf)



twice the voltage

highly-charged ions can be accelerated to high energy

(slide)

$T = eU + qU = (e+q)U$

p, d $T = 2eU$

He^{2+} $T = 3eU$ $(1e + 2e)$

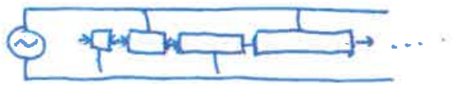
S^{16+} $T = 17eU$ $(1e + 16e)$

today: Vienna, München
AMS – accelerator mass spectrometry

a few words on beam pipe
vacuum, surfaces, electrodes, secondary e⁻

(2) Linear accelerators (LINACS)

idea 1924 Ising – idea
1928 Wideröe } first accelerators
1931 Sloan & Lawrence }
1937 Hansen & Varian discovery of Klystron (power amplifiers @ 0,1–10 GHz)
1946 Alvarez p-linac with 200 MHz resonators
1948 Hansen e-linac with 3 GHz klystrons



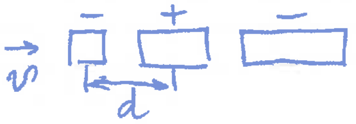
Wideröe structure

HF – high frequency

- acceleration of electrons, protons and HI

1. Wideröe-structure $\beta = 0{,}005 - 0{,}05$
2. RFQ-structure $\beta = 0{,}005 - 0{,}05$
3. Single-resonator (Einzelresonator) $\beta = 0{,}04 - 0{,}2$
4. Alvarez-Structure $\beta = 0{,}04 - 0{,}6$
5. Wellenleiter / Waveguide structure $\beta \approx 1$

- Wideröe Structure



- oppositely charged drift tubes
- acceleration in π-mode

slide

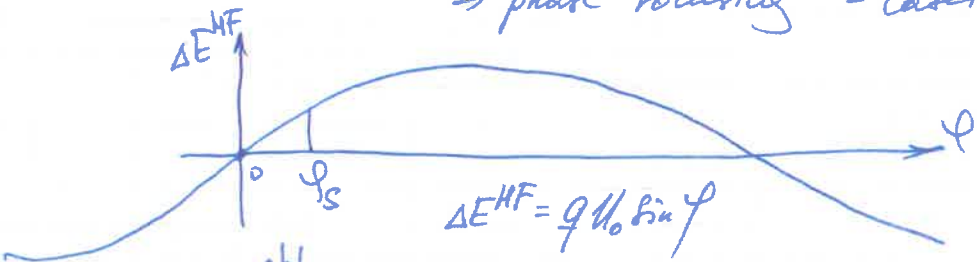
distance : $d = \frac{1}{2} v T = \frac{1}{2} \beta \lambda$ (π-mode)

↑ HF-period ↑ wavelength

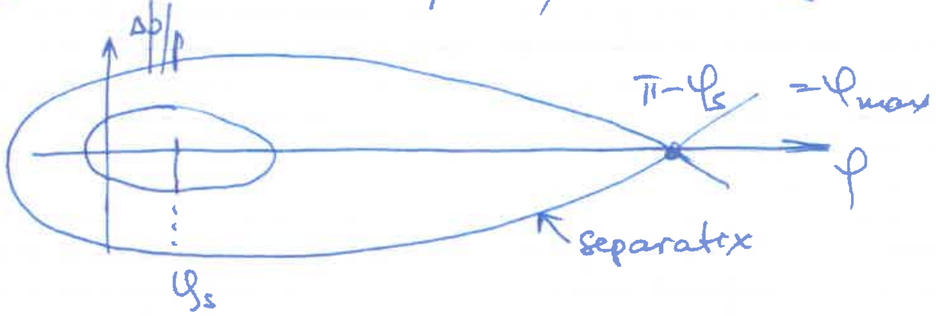
non-relativistic $d_i = \frac{1}{f_{HF}} \sqrt{\frac{i q U_0 \sin \varphi_s}{2m}}$ ← phase difference to $\varphi = 0$ (no energy gain)

properties :

transverse ~~phase~~ plane defocusing → ⇒ need for extra focusing magnets (QP) – later –
logitudinal plane : ⇒ phase focusing – later –



[discovered during design of synchrotron 1944-45]



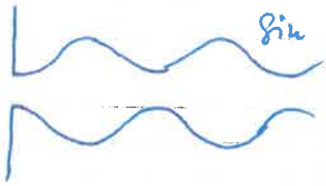
φ_{min} can be determined from $\int_{\varphi_{min}}^{\varphi_{max}} (\sin \varphi - \sin \varphi_s) d\varphi = 0$

φ_s – phase of synchronous particle

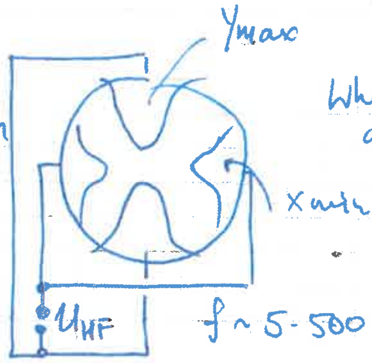
$\Delta E_s^{HF} = q U_0 \sin \varphi_s$ – average energy win of the bunch slide

- Radio-frequency quadrupole (RFQ)

1970 Kapchinskiy & Teplyakov



$l = 1-3\,m$



When x - min ; y = max and other way round ⇒ field gradient in longitudinal direction

$f \sim 5-500$ MHz

- transversal focusing
- adiabatic longitudinal focusing ~ 100% efficiency

$E_{p,HI} \approx 10\,keV/u \rightarrow 0{,}5 - 2\,MeV/u$

Continues or pulsed operation

Numerous applications, most frequently used low-energy accelerator.

③ Ring accelerators

+ most efficient use of cavities
- problem

$$p = eRB$$

if B-fixed ⇒ $p \propto R$ — cyclotron / microtron (e⁻)

if R-fixed ⇒ $p \propto B$ — synchrotron / betatron

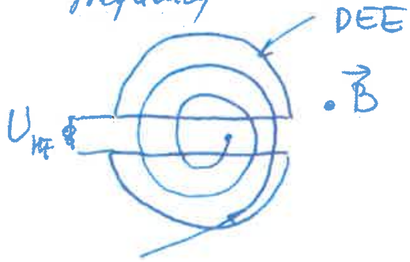
- Cyclotron
- classic

L3 ①

$$\omega = \frac{q}{\gamma m} B = \text{const}$$

↑ revolution frequency

if $\gamma \approx 1$ nonrelativistic approximation



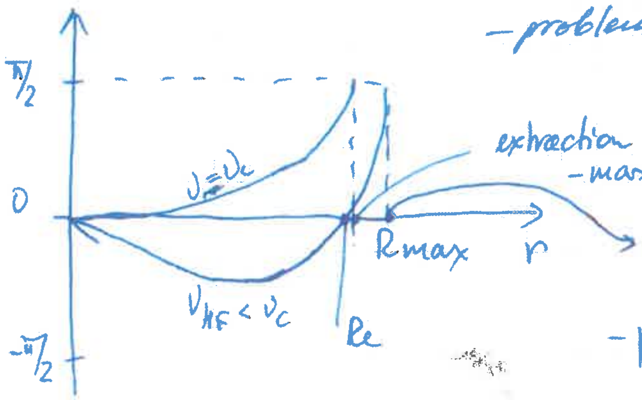
DEE - D-shaped electrode

$$\nu_c = \frac{1}{2\pi} \frac{q}{m} B$$

$\nu_c \sim 5\text{-}20$ MHz ~~B ≈ 1T~~

example: $B = 1T$, $\nu_c(p) = 15.2$ MHz, $\nu_c(d) = 7.6$ MHz

energy gain $= \Delta E = q U_0 \cos\varphi$ ($\varphi = 0$, is for $\Delta E = \max$)



- problem

ω- is not constant and ↓ with R↑
- relativistic mass
- reduction of B ~~at edges~~ away from center

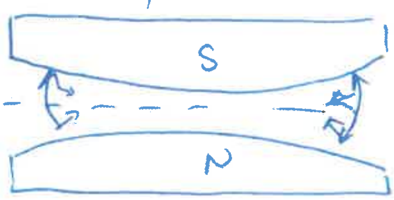
extraction:
- maximal separation in E
- maximal intensity

- properties

relatively high acceleration $U_0 \sim 400$ kV, ~50 turns

Example: $E_{max}(p) = 22$ MeV — Oak Ridge

- Stability



Lorentz force acts to ~~focus~~ keep the particles in the plane

- isocyclotron
- Synchrotron

→ Later (Principle of strong focusing)

L3 ② L3 ③