7

1

LINAC
→ not used rad ther?

- charged particles acceleration
- alternating electric fields (MHz - GHz)

β

p, I
- Wideröe (oldest) - drift pipe } 0,05
- RFQ - 4pole length mod
- Single Res. - cavity resonat 0,2
- Alvarez - coupled SR 0,6

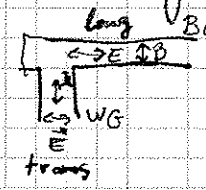
↓ higher β; circular; needed;

e
- trav wave - wave guide with iris diaphragms (disk loaded wave guide) } 1
- stat wave - coupled cav. res.

↓ higher β
NOT circular:
synchr. radid... → LINAC cheaper easier but many GHz
AND geometry not depend energy ... easily relativistic (light

Cavities and guides

- beam pipe $\xrightarrow{\vec{E}}$ $\odot \vec{B}$ $\otimes$ acceleration
- HF source → alternating E, B transported to pipe with wave guide
- Perpendicular coupling : wave guide TE_{10}
  beam line TM_{01}



↳ wave coupling can be at midd

Wave guides

both transversal

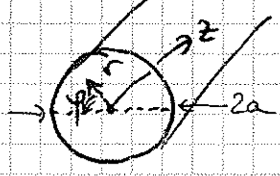
Vacuum : $\vec{E}\ \vec{B}$ → z , velocity c

⇅ can have longitudinal component (addit.)

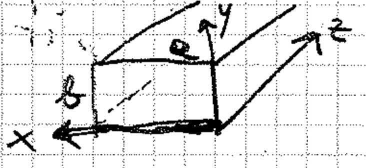
Guides : $\vec{E}_s = 0$, $B_\perp = 0$, $v_p > c$, $v_g < c$

Most:
TM_{01} -- $H_z = 0$
TE_{10} -- $E_z =$

Oscillation mode
- E long, B trans → TM_{nm}
- B long, E trans → TE_{nm}



cylindric wave guide



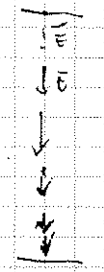
rectangular w g

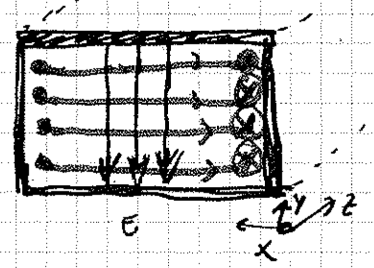
r, φ ← n, m : number of wave nodes in directions → a, b

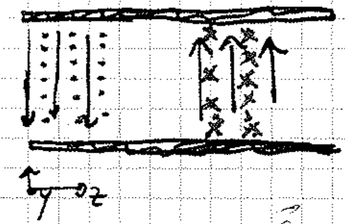
as accelerator within

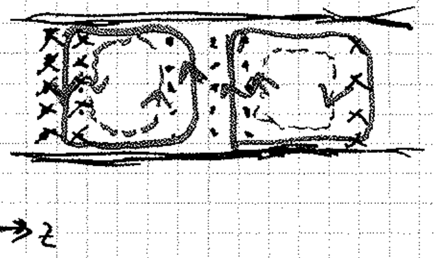
HF source $\xrightarrow{\text{coupling}}$ accel. TE_{10}

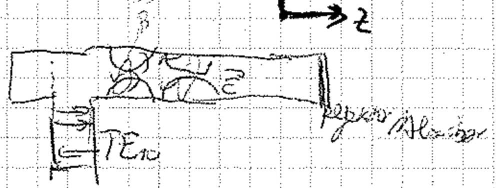
TE10











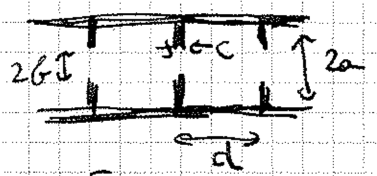
Disk loaded wave guide

$\vec{E}$ [illegible]: $\overline{v_\varphi} \leq v_{part.} < c$

phase not stable with particles → stabilize phase wave - part with extra elements (sync)

⇒ travelling wave acceleration (surfer)

$v_\varphi > c$ → reduce v_φ with iris



$\lambda_{HF} \propto d$

p, I: v_φ sync with v_p ⇒ increase d with E

e: $v_e \approx$ cte, d fixed is ok

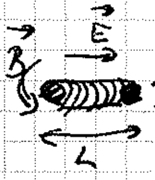
$I = I_0 e^{-kbz}$ → reduce b at larger z

attenuation ↦ constant $|\vec{E}|_{accel}$ at all pipe

*

Cavity resonator

Wg with metallic walls



(condensator + inductor)

conducting walls ~~not~~ conducting cylinder $\vec{E} = 0$

Reflection waves ↗

Length $\propto$ HF ⇒ standing waves

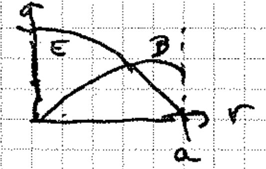
resonance condition

$L = \frac{n\lambda}{2}$ (cylindric) $n = 0, 1, ..$

n = 0, TM → L free

$\nu_n \propto \frac{1}{a}$

TM01 standing



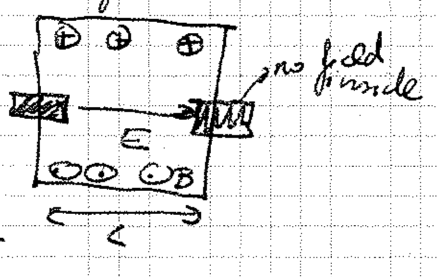
E max at r = 0

↳ if correct phase → accelerate particles z

Perforate walls

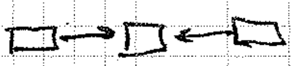
· Additional tubes constrain E

Single resonator

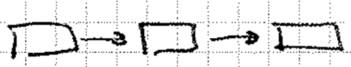


Concatenate SR ⇒ standing wave accelerator

π mode



2π mode

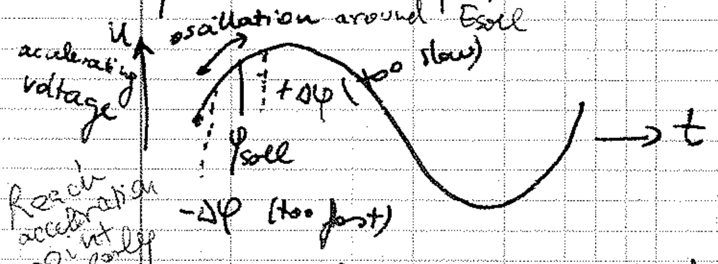


HF coupled to each cavity through slits wall (at B_{max} (a))
or over E field axial

Phase focusing in RF accelerators (not only linacs)

$U(t) = U_0 \sin(\varphi \cdot t)$

particles at φ, $U < U_0$ → on purpose for automatic focusing

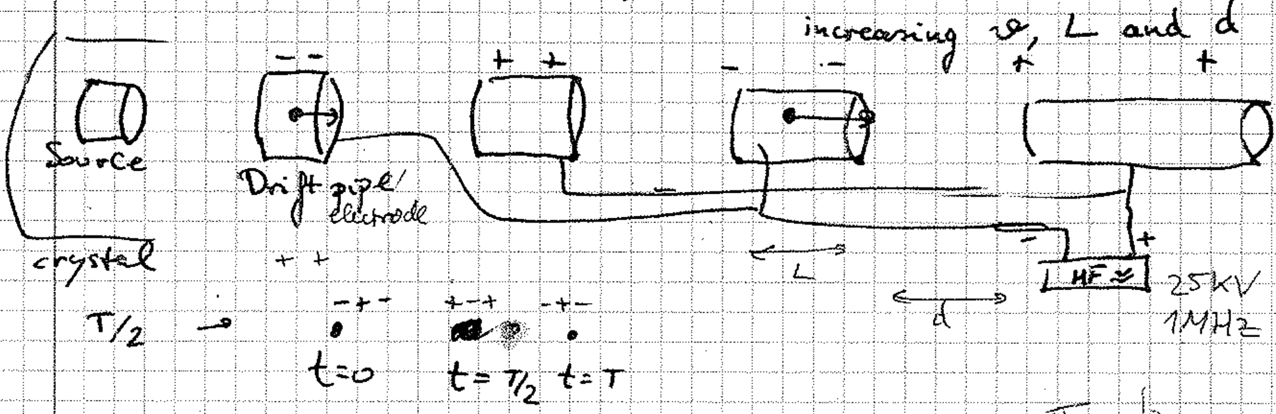


only for non-relativistic,
where $\Delta v \leftrightarrow \Delta E$
if $v \to c$: not anymore

energy focusing is imxt for later magnet deflection

Wideröe structure

- accelerating electrodes with RF alternating electric potential
- opposite phase → shielding ⇒ metallic hollow cylinder particles inside it, no field, during π phase
- synchronize ~~RF~~ ↔ particle between electrodes (each two)



π mode

$L = v \cdot \frac{T}{2}$

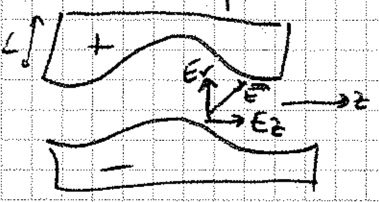
(not relativistic) → $\Delta E = \underset{\text{n electrodes}}{n} \cdot q \cdot U = \frac{1}{2} m v_n^2$ → $v_n \propto L_n \propto \sqrt{n}$

$v = c$ → no geometry change needed

RFQ accelerators

Resonant structures with ELECTRIC ! RF quadrupoles (rods), sinus-like longit.

~~distance~~ length = poles varies symetrically
⊥ poles ‚‚ 90°



oblique E < radial: transversal focus / longit : accelerates

up to 100 mA protons

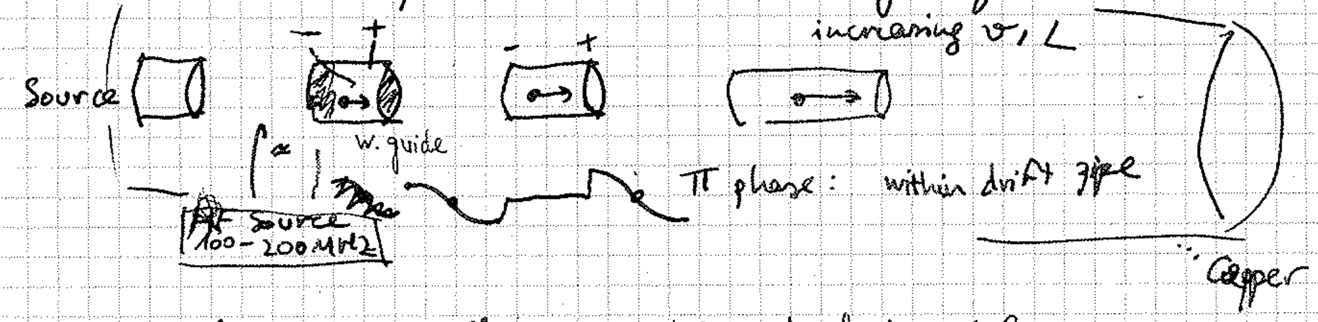
Fel independent on v

Not relativistic → increase meander with v, size depends also RF 10 - 500 MHz
3 m

Alvarez structure

higher E → long drift pipes // high RF → losses

- Linac with cavity resonator ⟶ standing long. $\vec{E}$



Alvarez : leave out walls, use metal instead of crystal
+ HF wires not on drift pipes, just as w.g.
TE wave
2π mode

for heavy ions

Electron Linac

wave guide

travelling wave → wave pulls e^-, fades at end
standing wave → wave reflected, e^- surfs over waves
} both cylindrical ⇒ resonator cavities (cylinder)

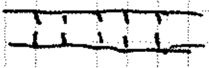
Energy
$E_{kin} = e_0 \cdot E \cdot \Delta z = e_0 \cdot V$ (constant field)
$E_{kin} = e_0 \int_0^l E(z) dz$ (variable ") l: active length

$E_{z}(\varphi) < E_{z\,max}$, loss walls, HF loss e^-

Travelling wave

beam pipe metallic, disk loaded wg

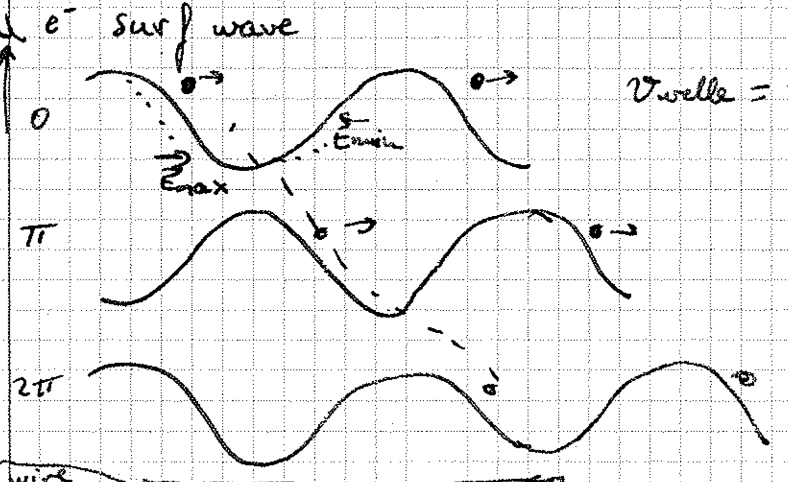
iris 5 - 10 cm



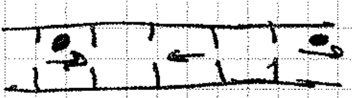
perpendicularly: TE_{10} - - -> TM_{01} wave , $v_p \leq c$

e^- surf wave

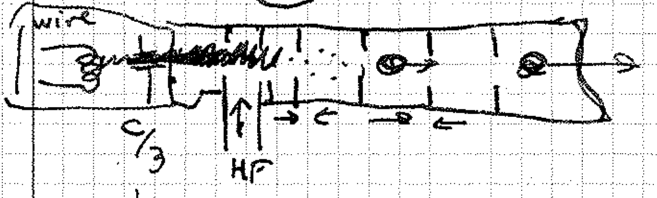
ll height and not steepness in the accel.



$v_{welle} = v_e$



phase focusing
~~lateral~~, longit., timing



e^- bunching
3 GHz
+ microsecond long macropulse

↳ 0,99c : 3 MeV

first ~~resonators~~ resonators special geometry slower v_p (Buncher)
end → wave dump / recycling pipe start
beam exit window, protects vacuum, e^- cross

Standing wave

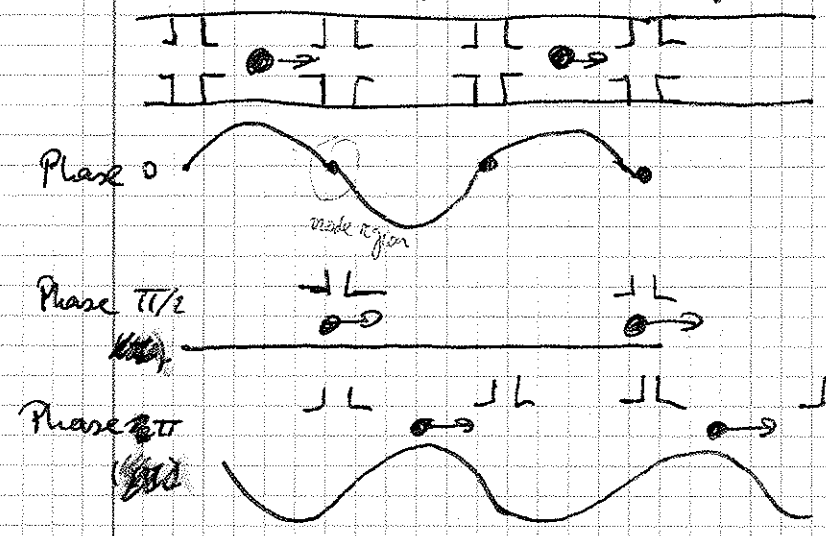
Different configuration of disks, cavities, and RF coupling

Serial connection RF cavities (SR)

End of pipe closed, reflects wave, "no" losses

coupling points for RF transport : no $\vec{E}$ (nodes)

∴ also laterally, then less length needed



acceler max E

$E_1 = E_0 \cos(\omega t - kz)$
$E_2 = E_0 \cos(\omega t + kz)$
$E_1 + E_2 = \underline{2E_0 \cos kz} \cos \omega t$

drift constant E within drift pipe up to next cavity

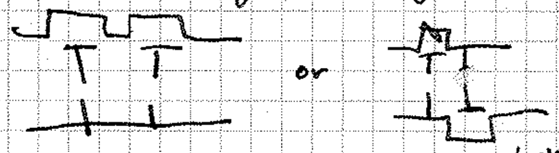
acceler max E

bunching at beginning through geometry change (== TW)

$v \to c$, v kt with E c, Length kt

focusing inductors lateral bunching → higher intensity

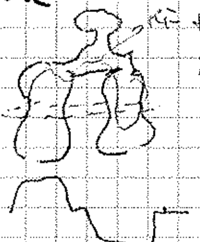
lateral coupling points



seitliche Kavität Feld = 0

rectangular wave
3GHz harm.

↳ no accelerat make it 0 and laterally nodes

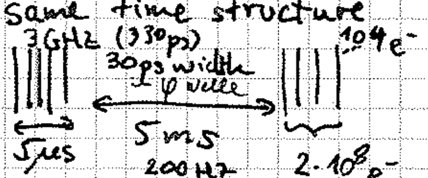


Comparison

travelling wave

- ~~Larger~~ (~~Same~~ E)
- 35% en. acceptance
  ↳ good bunching
- $\Delta\nu$ not critical (no resonance condition phase)
- small ΔE, no need for ESS
- RF recycling ! power
  ∴ useful > 20MeV,
  where limits RF source power (magnetron, klystron)
  coupling at end necessarily !
- higher tuning req., especially if E_e change
- used 4 - 20 MeV

same time structure



- amplitude slope depends load (heat loss, e^- energy)
  ↳ only 10% accept.

standing wave

- higher requirements for ΔE and dependence $\nu \leftrightarrow$ ~~Accel~~ accelerat
- RF intensity, E depends more (affected) on beam loading phase (load during)
- higher vacuum requirements, sparks, high E
  (10^x) 10^{-6}, ~~...~~ hPa
- + lateral RF coupling → short
  good for nozzle, gantry
- $\frac{3MV}{m}$ air 3MV/m sparks 10^6 V/m → resonance
  + E much higher ⇒ e^- dark cu
  when RF_{on} but canon off
  ↳ extra surface treatø

- For Co^{60} subst. is ΔE not critical → useful there, short, perpend., no need deflection
- For e^- therapy, bigger ΔE → need necessarily deflector + ESS

Espread ↗ / rectangular wave ↗ surface quality → higher E? → higher distortions
↗ in wave Standing

Medical e⁻ LINAC

$\boxed{8}$ * ^{60}Co, ^{137}Cs fixed ↔ X-ray tube vary V, but technical limits
art / quality ↳ just for surface

⇒ need for free parameter: E, $\bar{Z}$

- most: 4 - 6 MeV γ, E combino, also e^-
- modern: 2 - 30 MeV e^-, 4 - 25 MeV γ (several steps) ← technically diff.
- customizing region (less side effects) → colimator variable openings, iris dynamic

↳ nozzle: contain elements for field / isodose formation

block collimator / multi-leaf collimator

α, d free p., type, E reproducible (live monitor) ← depth dose prof., fall-off lateral, symmetry, homogeneity, ~~dosered~~ doserate (Gy/min), no γ contamina, field size, robostness, easy

Monitors: ← CT, Portal Imaging System, 2 X-ray panels

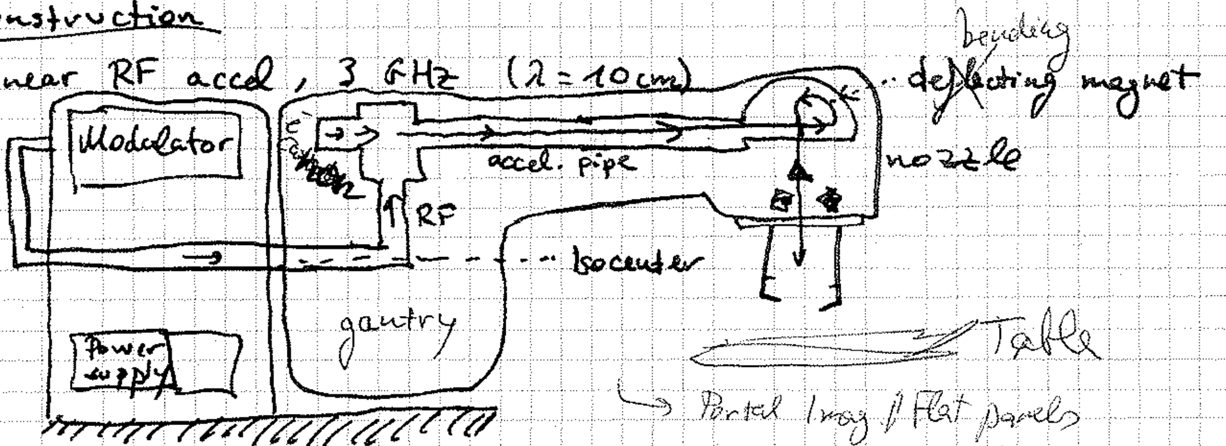
- Only Photon machines (2-4 MeV), ^{60}Co subst., Stehwelle standing wave

↳ accel ⊥ patient, 30-50 cm, 150 kg, no magnets ↓, no ESS → cheap

↳ in robots, free move

Construction

Linear RF accel, 3 GHz ($\lambda = 10$ cm)



Modulator: RF source, electronics, may be also separate room
↳ wave guide to beam pipe

Gantry: rotatable arm → vacuum system
↘ cooling

↳ Canon: e⁻ source

Nozzle: magnetic deflector (bending), photon target, compensator (flattening filter), light snipe,
beam monitor, collimator
↳ verification system

focusing
bunching
homogen.
collim.
monit.
γ genera

Large shielding → tons
↳ gantry: mm precision around isocenter

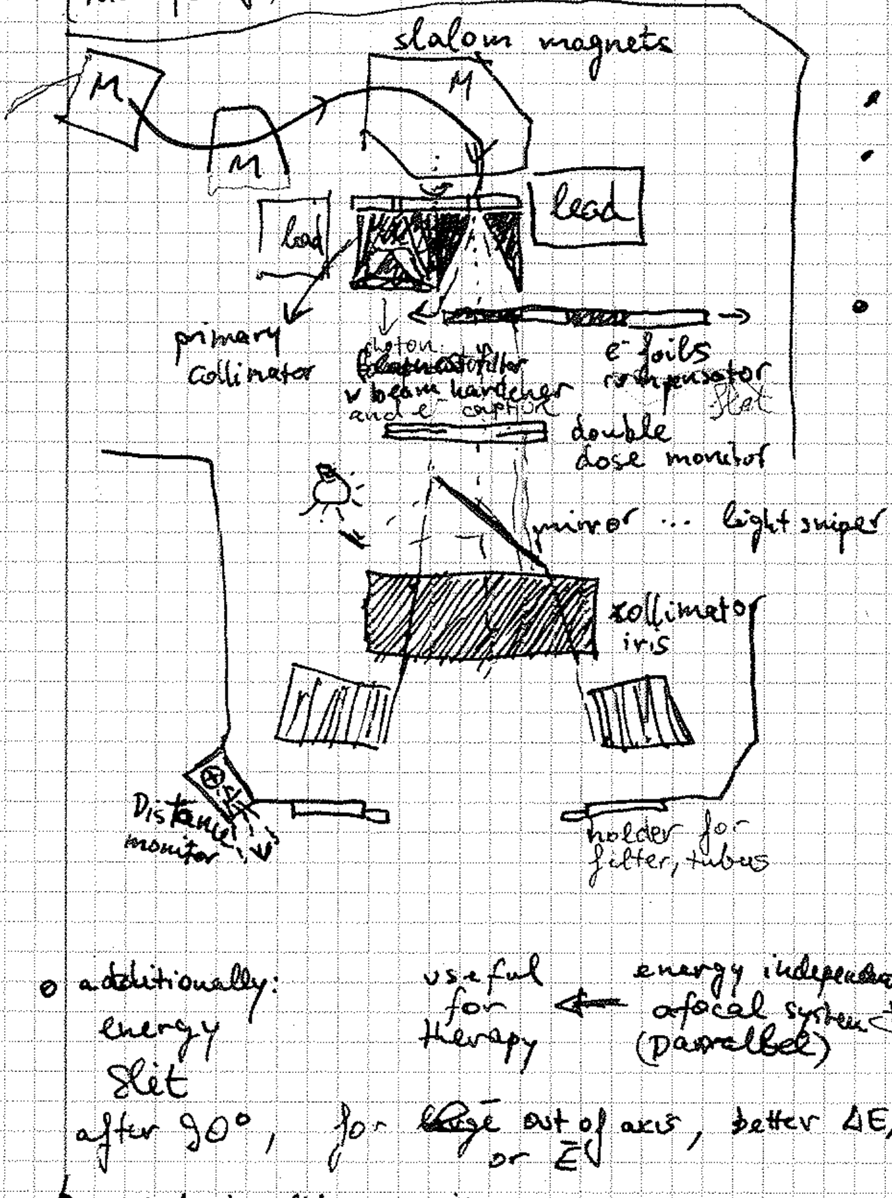
Nozzle e⁻ mode

pulsed pencil beam (mm), no ESS yet

→ dose profile depends on α, ΔE

↳ minimize interactions e⁻ → change spatial/energy structure + contaminate γ

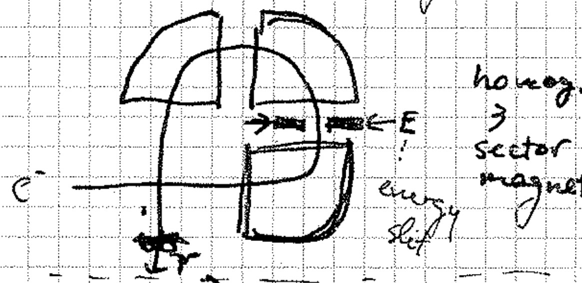
⇒ deflect first, but focused, bunched
⇒ first collimation
⇒ homogenize, symmetry, independ. lateral separ. center (field compensat
⇒ monitor position, "
⇒ dose rate monitored
⇒ collimation (field formation)
(idem for γ)

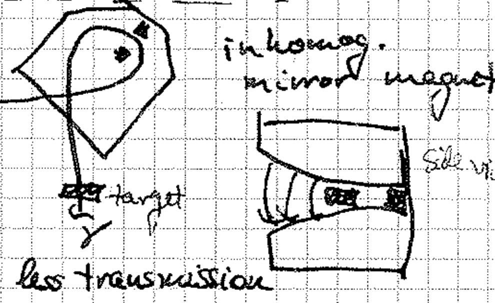


Deflection Bending

- affects ΔE, Δα, focus point
- 90° magnets → bad if ΔE ≠ 0
  ↳ no focus; no achromat
  ↳ Dx ∝ ΔE, no homog. depth profile
- Better 3 of them:

270° magnet, focuses beam even with ΔE to a point (but divergent)
+ more if Δα initial
↳ correct with mirror magnet





- additionally: energy Slit

useful for therapy ← energy independent afocal system (parallel)

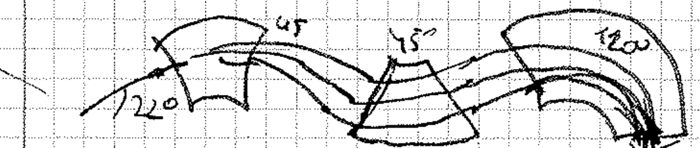
after 90°, for ~~large~~ out of axis or E, better ΔE, but less transmission

current at slit → monitor

↳ Standing wave: 1-3% ; open slit 10% (photon mode) < not that important / more rate, later target absorp

- modern: slalom magnet → 2 × 45°, not focusing, 1 × 120°
  ↳ double focusing, achromatic
  ↳ due to space restrictions in trav. wave accel, to spare height and compensate oblique long w.g.
  + better ΔE tw, no need for ESS (just 4 security)

but need 270° for energy selection!! at least e⁻ therapy



… 90°

Usually: 4 pole duplett used for focusing before deflecting magnet

Homogenization

correct ΔE, α, but too small (focus mm) → (beam 1m cm)

⇒ has to be extended + smoothed (field homog / compensd)

1) scattering foils 2) magnet scanning

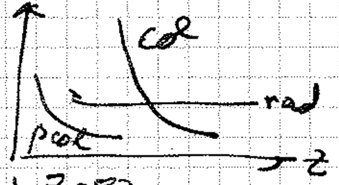
Scattering foils

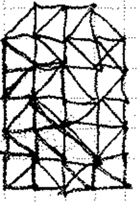
thin foils → still ↑ΔE ($\overline{E}\downarrow$), energy straggling (↑) + bremsstrahlung

↳ choose (heavy metals) material minimizing side effects

$S_{col} \propto \frac{Z}{A}$, $S_{rad} \propto Z^2$, $\overline{\theta}^2 \propto (Z+1)^2$

$S_{rad}/\overline{\theta}^2 \approx ct$, $\frac{S_{col}}{\overline{\theta}^2} \sim \frac{1}{Z}$





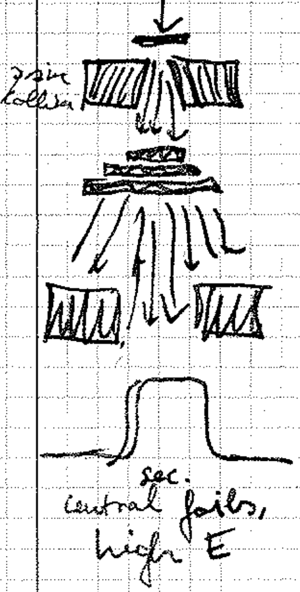
⇒ Thus, use high Z: tungsten Z=74, lead Z=82

for maximal $\Delta\theta^2$ and minimum ΔE

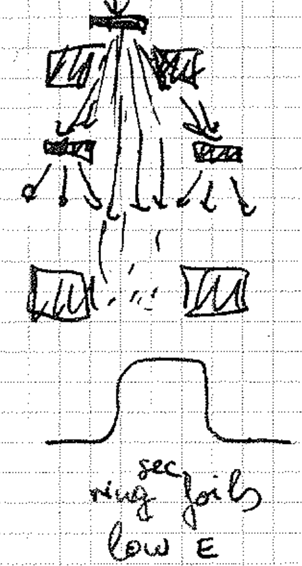
single f.:
- thick
- Brems
- $E\downarrow$
- straggling

- Still $\overline{E}\downarrow$, $\Delta E\uparrow$ compared to after ES
  thickness → Bremsstrahlung ($S_{rad} \propto t$, contaminates)
- The higher E → the thicker foils and $\angle^{\overline{E}}_{\Delta E\; S_{rad}}$ thicker because $\Delta\overline{\theta}^2 \propto \frac{1}{E^2}$
  ↘ several sets (E)

- single foil → Gaus, dose rate loss after homog., compromise ∠ size / rate / side effects
- double foils avoid this problem, less thickness, less $E\downarrow$ (less S_{rad}), higher rate
  + better homog → larger fields
- most: same primary scatterer for all E, close to ES, same compensator
  - × low E: ~~too~~ high effect ΔΘ, too outer
    ↳ secondary foil as "hollow" ring
  - × high E: not enough $\Delta\overline{\Theta}$, too central
    ↳ secondary foil central thicker

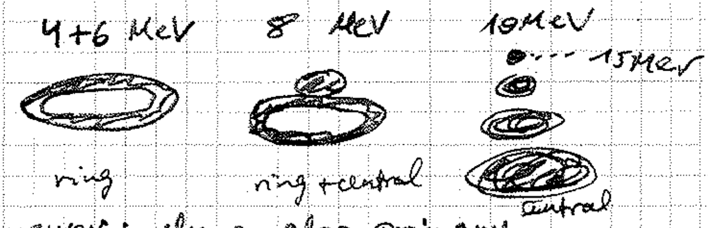


sec. central foils, high E



sec ring foils low E

prim: 0,1 mm tungsten W
sec: 30 μm thick lead Pb



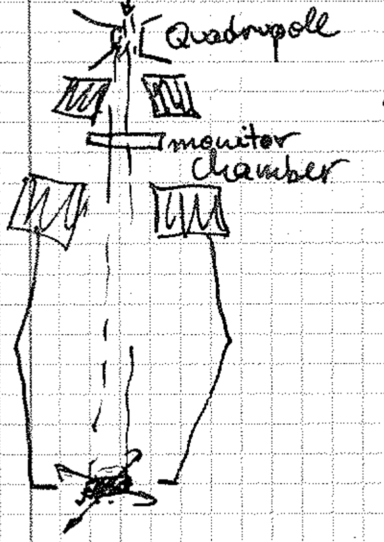
→ newer: change also primary
carousel up to 7

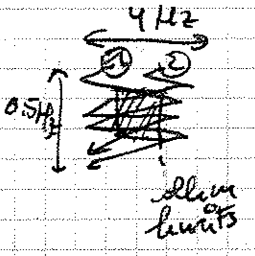
Important condition: stable position, α, Ebeam wrt foils
otherwise over/under compensd

↳ **monitoring** E, position based on energy slit ~~abd~~
dose rate monitor

Scanning

E very high, too side effects → use magnets instead < de focusing inductors / scanning magnets





scanning
over the field size + collimator
because of Gaussian shape, otherwise border effect (Paint)

less interactions nozzle, less straggling, $\overline{E}\downarrow$, Srad
better dose profiles at high E than foils at low
but: rest wave effects, less homogeneous
depending on scan frequence
and: more complicated dose monitoring
not possible motion organ
security issue 4pole → 1 burning point InterLock

Not offered anymore

	1 foil	2 foils	Scanning
Energy loss $\overline{E}\downarrow$	high	mid.	0
spread ΔE	large	mid	0
depend. $f(E)$	large large foils	low	low
Bremsstr. ratio Srad	< 10%	< 3%	<<
Field homogen. compensation	mid	high	rest wave
" size	small	large	large
Dosimetry	easy	easy	compl. — I channels recording
technical complex.	small	small	high
motion	yes	yes	no

Collimation e^- beam

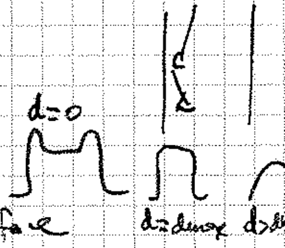
multi stage collimator

also for e^- mode thick

1) primary collimator, conic, between two scatt. foils, constrains max cone size
2) movable aperture for rectangle/quadr field, ⊥ position in half
~ 20 cm lead/tungsten
3) e^- collimators : lateral field constrain of already homogen. < tubes / trimmers

Tubus

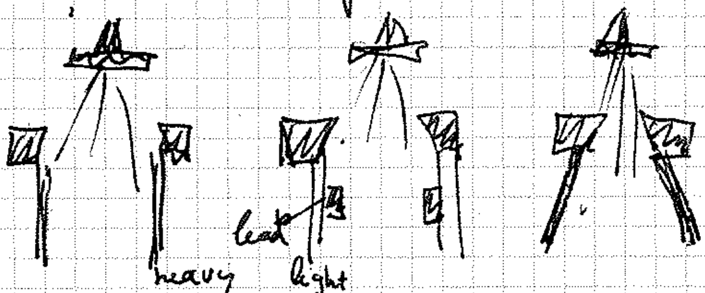
metal tubes/walls, scattered, divergent e^- are < parallel / divergent
↳ compensate Gaus fall-off for homogeneity — air scattering Δx
↳ less weight of compensators ~~apertures~~ flat filt
But: change direction, also E loss
↳ different E spectrum at margins, max to the surface



- Smoothing depends on field size & separation collimator border – patient
  ↳ Dmax closer to surface, more side effects skin
  ↳ contaminated w Srad

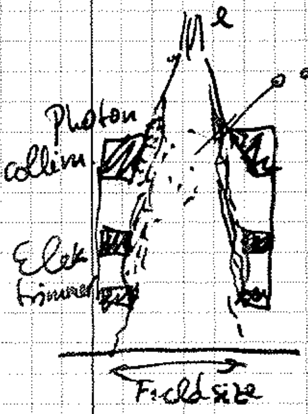
modern: → lighter, ~~movable~~
  ↳ small metal trimmer inside tubus
  ↳ more separat. (10cm) to patient

⊖ limited number field sizes → take care about custom idea!

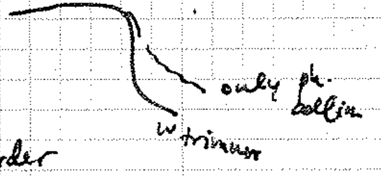


Movable e⁻ trimmer

- 2 pairs of half iris (total heavier, but single lighter than tubus)
- 0,9 m from focus (10cm over isocenter)
- custom sizes up to 30 cm, ~~gateable~~



air ~~Scatter~~ volumes
↓
loss ~~Scatter~~ central e⁻
loss rate border
↳ not that homogen.
↳ new collimat. needed close to patient
cut borders, ⟸ Phot. coll. size



- best geometry for filling border
- NOT ▨ but ▣ extra air
- E spectr. not change signif.

(applicators)

- movable collim restrict field without E spectr modificat. ⇄ tubus
- several trimmer hang below ph-coll (more open than final field)
- up to 20 MeV: ~10 cm smaller for e⁻ than γ
  30×30cm²   40×40cm²
- extra upper trimmer for lateral leak avoid, + lower shadows
- dosimetric properties depend on Z, E
- lead, tungsten, sandwich light/heavy (less Srad)
- only few mm thick (stops e⁻), to be light
- not close to patient → larger half-shadows, no filling borders
  ↳ but allow moving target

8.4 **Nozzle in γ mode** 6

e^- converted γ with – tungsten target $Z = 74$, $\rho = 19{,}2\ g/cm^3$, $\varnothing 2cm \times 2mm$
sandwich heavy metals

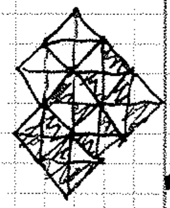
Bremsstrahlung (S_{rad}) $\propto Z^2$ ↔ losses $S_{col} \propto Z$ ⇒ better high Z, specially high E ($\frac{S_{rad}}{S_{col}}$)

$\propto$ thickness

↳ but also higher self absorption

- upper limit: e^- range, $d > R_{max}$ only losses
- thin: $d << R_{max}$
- thick: $d \sim R_{max}$ (15MeV, W, 2-3mm)

↳ all stopped, S_{col} → target hot ⇔ S_{rad} not



→ 10MeV e^- → 50% S_{rad}, but 10kW → cooling also

→ 100 keV e^- (X-ray diagn.) → 1% S_{rad} ↔ 99% S_{col} ⇒ cooling needed

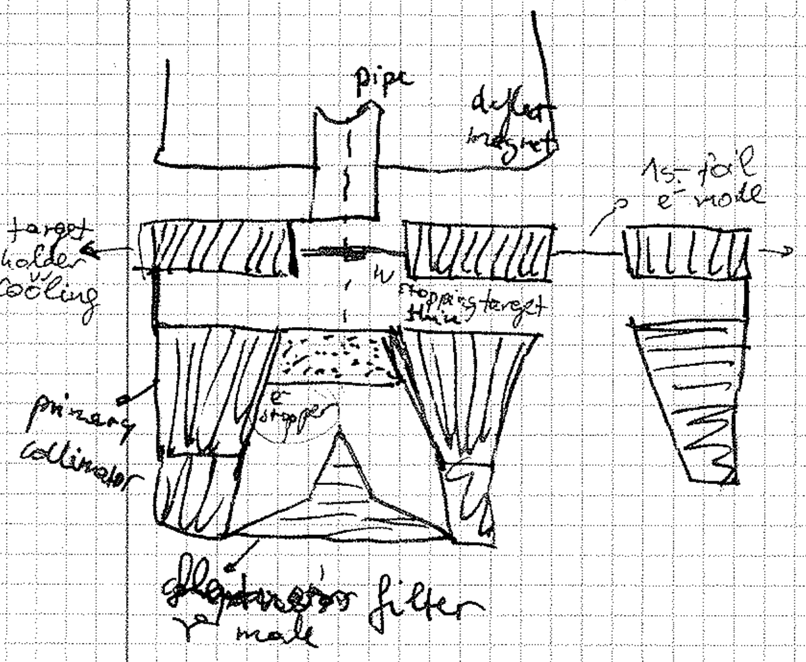
- target holder: Cu, heat conducting ⋯→ HP water
- cooling == security
- thin: cooling not that critical, but later $\bar{e}$ beam stopper
  stopper → light materials, avoid (γ hardening and) γn prod: C, Al before γ ~~compensator~~ flatness filter, in primary collimator
  $S_{col}\uparrow$, $S_{rad}\downarrow$
- thickness affects quality γ spectrum

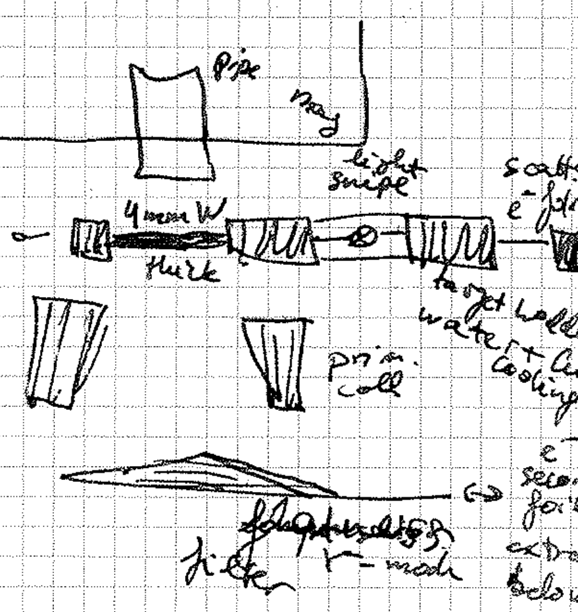
↳ thin: less soft γ, e^- not slow, less interactions, higher $\bar{E}_{\gamma}$ and half range tissue at same E_{e^-} than thick ones

\+ beam stopper hardens also (low Z), absorp low E ph.
but, thin, for γ, does not attenuate too much?

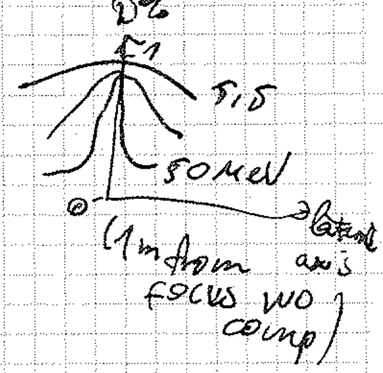
↳ thick: multiple interactions, $\bar{E}_e \downarrow \to 0$, slow, $\bar{E}_{\gamma} \downarrow$ (excessive!), γ scattering
4mm W w. cooling

\+ γ scattered with less E_{γ} < Pair prod / Comp scatt → less quality



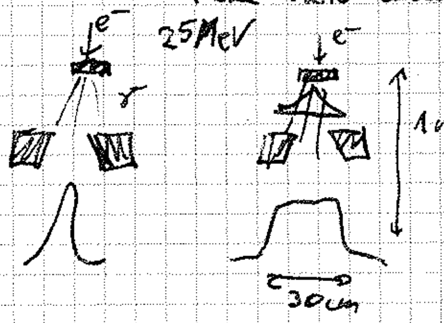


Homogenization of γ bunch



- higher E_e → E_γ more concentrated on axis
  forward focused Bremsstr.
- continuous E_γ spectrum 

↳ need for conus ~~flatteners filter~~ to homogenize
  $E_\gamma(\alpha)$ … forward high E, lateral lower
  : take into account 4 construction one

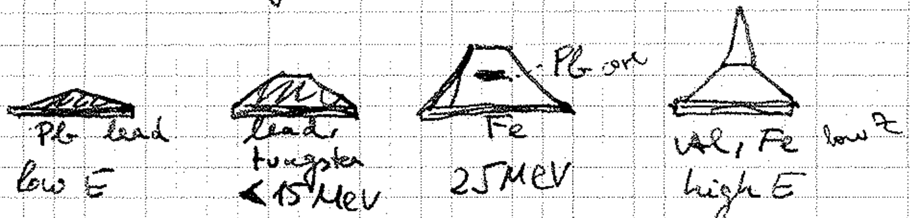


1) scatter beam cone
2) lower $\overline{E_\gamma}$, $E_{\gamma max}$ (Compton, PP)
3) harden beam (higher $\overline{E_\gamma}$)
4) attenuate intensity
5) contaminate e^-, n
→ dominance depends on Z, ρ, t

- high Z → CS, PP soften E_{spec}; 50% PP lead 5MeV E_γ ⇒ 511 keV!
  80% 15MeV
  ↳ dose profile steeper
  ↳ maximum to surface, skin dose ↑
  ↳ high ρ: high Δd
  but good homogen.
- low Z (Al, Fe)
  ↳ harden beam γ spectrum central axis → virtual higher E_γ prof. → E_e
  ↳ but: stark ΔE wrt borders → take into account for dose profile!
  ↳ and: very thick (25cm) → not fit, aberrations, …

Better: combine low Z materials
- cylindric b hardener Al + conus iron
- × take into account ΔE
- × Compton e^- created low E → skin dose ↑, $D_{max,t}$ ↓
  ↳ some: magnets, beam monitor

Solutions

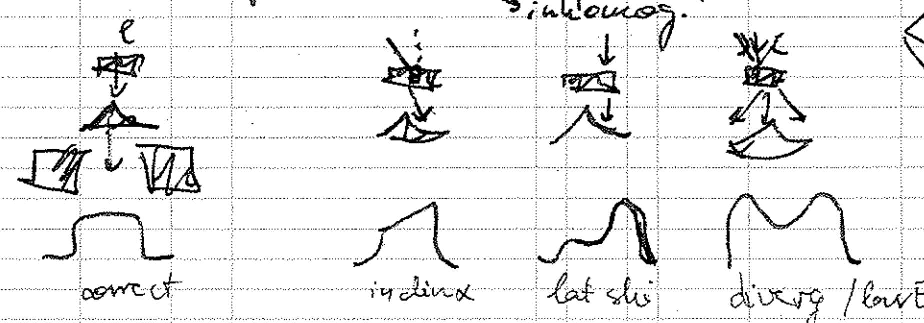


- high E_γ → nuclear photoreactions → activation, n
  ↳ choose material avoiding this (threshold high, σ ↓)
  low $t_{1/2}$
  Cu not allowed (β^+ n ^{62}Cu) … n, γ
- ~~flatteners filter~~, attenuate 2 – 10 + S_{rad} e^- → γ (< 50%)
  ↳ power γ mode ×10/100 × e mode
- now: computer optimized sandwiches Fe, Ni, W, Pb
  ↳ several E_γ steps: carrousel, positioning ∞ interlock

- ~~[illegible]~~ even more sensitive shifts, $\Delta\alpha$ beam than in e^- mode
  unfocus, ΔE, magnet current
  divergence

⇓

bad compensation → asymmetry → inhomog. ⇒ need monitoring < position, energy, dose rate



Collimation of γ bunch < conventional / multi-leaf

Conv
- "convergent" coll → slits directed to focus ... Bremstarget point, 2 steps
  1) prim. coll below ~~[illegible]~~ Brad target, conic, fixed, defines field max
     ↳ made of W / Pb
  2) config. coll below ~~flattenes filter~~, defines actual field, rotatable ← 4 half apertures, heavy metals, 2 pairs (x, y)
     ↳ made of W, sometimes (E) extra Pb wall, Al (low Z) (reduce scatt. radix)
     ↳ separated slits, ⊥ freedom, circular rotx, inner wall ∥ focus

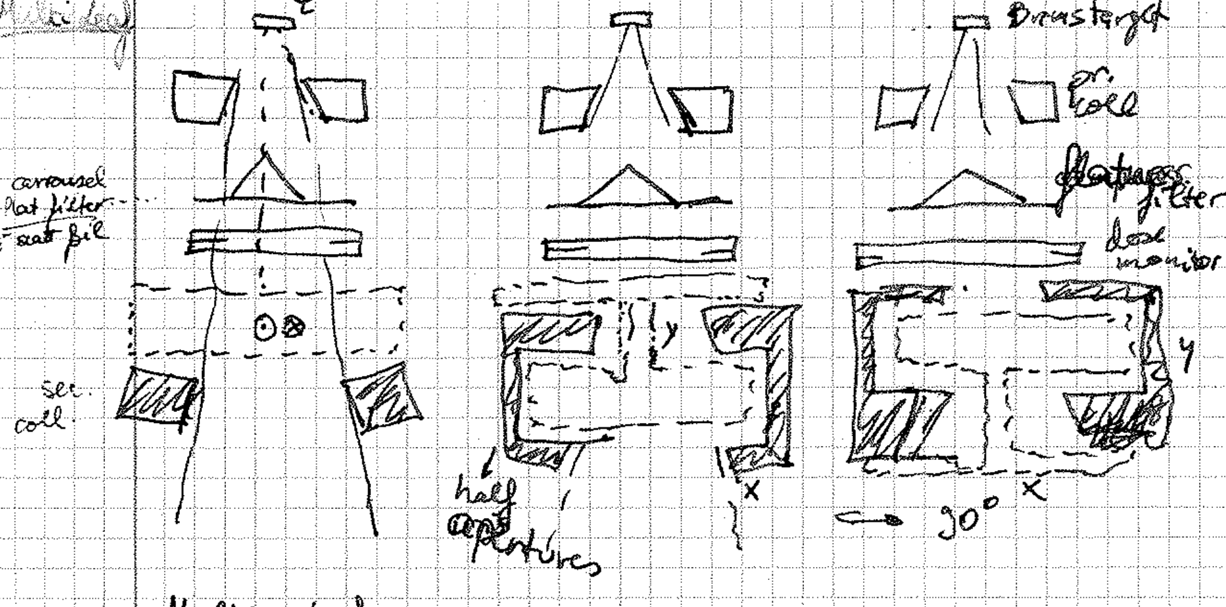
Most: different distances to ~~flattenes filter~~, over each other

One: half ~~apert~~ aperture up/low side trimmer W, Pb → good coll, fieldsize fall-off

but: backscatter monitor → field size dependence, asymmetry $\dot{D}$ when rotating wrt dose monitor, especially when in bottom (small dist. to coll)

also: new can overtravel over self field half (opposite side)

Multi leaf



Opening / closing of half apert.
$\dot{D}$ changes
- by apert change
- backscatter monit.
- volume dependence scatt γ in patient

x, y diff distance
x·y != y·x
not same dose

Multi-leafs

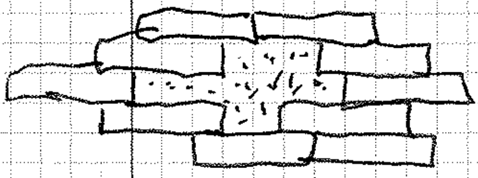
- target volume not regular → MLC, up to 120 leafs parallel, W
- some just one of two pairs
- manual/remote move, custom shapes field
  also over field middle

- below conv coll. as standalone aperture or directly in nozzle

⊕ geometry, beam field is kept, no extra / custom ... chamber to point source, not 4 half apertures anymore

⊖ backscatter monitor ⊖ α not defined aperture, but depends on leaf

→ therapy / dosimetry more difficult, D (leaf position, d monitor, ..)



Often: just replace x-aperture of conv.

Compl: double-focused

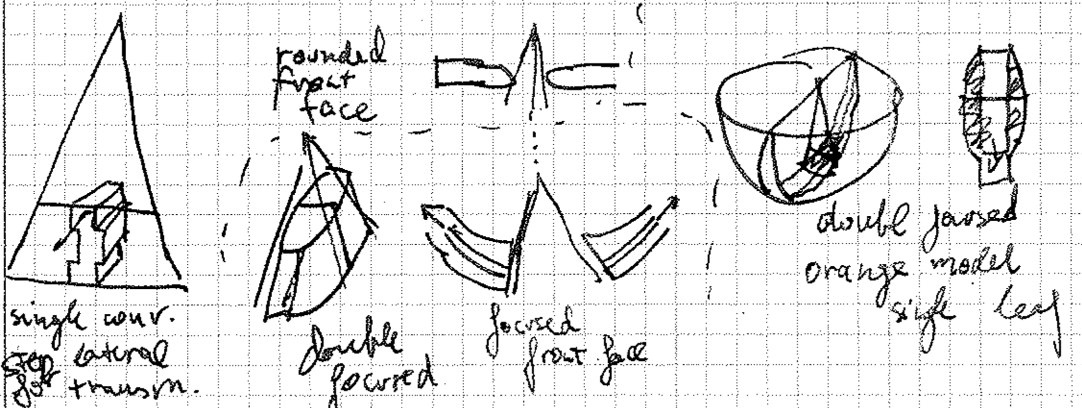
↳ move∅ on spheres sections

↳ some room → leak radiation

↳ incorporate steps lateral alternat.

- cheaper: single focus, renounce front face sphere driving, just parallel move∅
- also lateral steps, minimize transmission, (but w/ spröde)
- easiest: cubes, ∥, but oblique transmission inner side

need less spaces than focused one



→ move∅
↓
leave free room

leak! transm.

- transmission / half penumbra problems longit.

+ single focus (not conv) problem front face ⟹ circular: focus ok

parallel move∅ → no focus possible → round front face, always tangential

↓ indepd. field size

but: additional transmission (up to 50%)

↳ worsens fall-off wrt 2x focused

... try to cover leafs with conv. collim.

half penumbra > and transmission

x To avoid (despite steps) leak transmission

↳ additional trimmer: satellite aperture W, cm (backup)

↳ if MLC replace ~~x~~ and y, are satelites inext longit step

leaf 5-6 mm thick, 1 cm wide

- Computer controlled → complicated targets, many fields, optimized TPS

Potentiometer → feedback motor step leaf

or:
mirror each leaf, CCD → remote control / tuning

- TPS: dose profile, time (MU), reduction of scatt γ due source leafs

+ backscatter monitor, change geometry leafs, ...

- Challenge: IMRT (condition: MLC exist)

↳ move∅ leafs changes field form → custom 3D dose map and varying intensity (time), + gantry angle

⊕ if OAR close

< Step and Shoot, sequential for each config. leafs (and α)
< dynamic, move leafs during seq. or angle

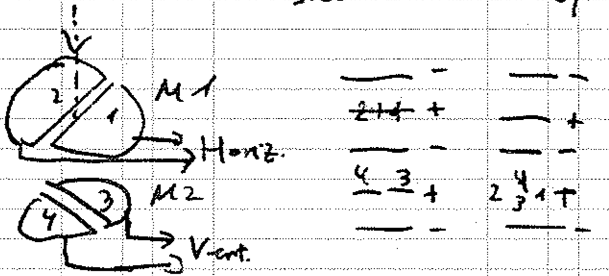
→ special planning, QA, dosimetry, patient positioning

working FFF: flattening filter free

→ less motion compensation during fraction, if stereo X-ray tracks it

8.5 Double dose monitor system

- Below flat filter / compensator / scatt foil e⁻ homog. → beam monitor
- security: twin system, independent ionisation chambers
  ↳ each divided in sectors (half e.g.), ↳ 90° rotated
  ↳ sometimes: circular sectors
- measure dose as sum; check symmetry as diff, auto beam tuning
  ↳ amplified signal for ↗ of quadropole, 3-sector magnet
  ↳ horizontal and vertical symmetry (∥ LINAC)
  some: transversal vs radial symmetry



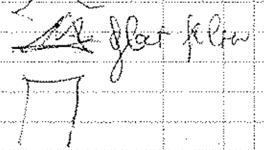
- second monitor, security → Δ12 ⇒ Interlock
- sum signal 2/4 for dose rate control and dose measurement
  ↳ after some level of charge → counter++ ; "click" ⇒ MU
- 3rd security: clock limiting max irrad. time, assuming controlled $\dot{D}$
- open/closed I-chamber
  ↳ independent T, pressure but absorption massive walls, E↓, spread spati
  mostly used for γ
  ↳ depend p, T; internal global cooling, connected T ⇒ interlocks, no problem anymore / still p
  mostly for e⁻, dose, dose rate, avoid E↓ thin
- medical physicist recheck regularly, key stone for dose, security, quality
  ↳ field size dependent MU tables

$$\dot{D} = \frac{\langle D\rangle}{t} = \frac{E}{m\cdot t} = \frac{N\cdot E_e}{m\cdot t} = \frac{N\cdot E_e}{\rho\cdot A\cdot d\cdot t} = \frac{20\,\text{MeV}}{10\,\text{cm}\cdot 1\,\text{g}/\text{cm}^3\cdot 10\,\text{cm}^2}\cdot\frac{N}{t}\cdot\frac{e}{e} = \frac{20\,\text{MV}}{1\,\text{kg}}\cdot I = \frac{2\,\text{Gy}}{\text{min}}$$

$$\rightarrow I = \frac{2\,\text{Gy}}{\text{min}}\cdot\frac{1\,\text{kg}}{20\,\text{MV}} = \frac{2\,\text{J/kg}\cdot 1\,\text{kg}}{60\,\text{s}\cdot 20\cdot 10^6\,\text{J/C}} = \frac{1}{6}\cdot 10^{-8}\,\text{A} \approx 2\,\text{nA}$$

$$\langle I\rangle_{LINAC} = 200\,\text{Hz}\cdot\underbrace{\frac{5e^{-6}\,\text{s}}{330e^{-12}\,\text{s}}\cdot 10^4\,e}_{2\cdot 10^8} = 200\cdot 1.602e^{-19}\,\frac{\text{C}}{\text{s}}\cdot 2\cdot 10^8 = 6\,\text{nA} \longleftrightarrow 0.1\,\text{W}$$

~~Flat filter~~ Bremsstrahlung ⟹ modern take into account ~~...~~ + MLC

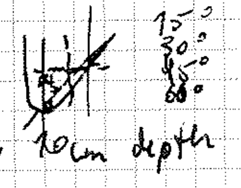


1) less I
2) diff. beam hard
3) e⁻ contamination

1) higher $\dot{D}$
2) not distorted E spectrum

8.6 **Wedge filter** (FOR γ) { external / internal/motor / dynamic } compensate tissue absence

- attenuate γ field one-sided ↳ avoid hot spot in some regions
- triangular shape, heavy metal, Pb (ext/int)
- also used in X-ray diagn (irregular target, for = optical thickn film)
- 2nd option: individual compensator
- most: Satellite holders with external wedge filter
  - ↳ 40cm to patient, but can be adjusted → changes atten. factor, fans

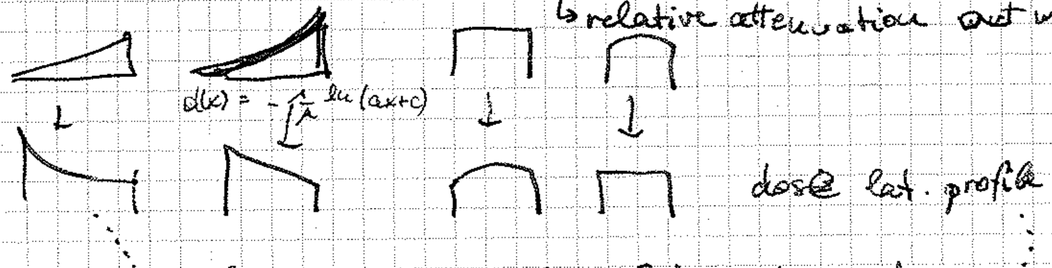


External

< ~~Ke~~wedge filter angle (isodose) → dose 150° profile inclind, NOT mechanics → secant ± FS/4, 10cm depth

" " factor → ratio D_w central axis depth 5-10 cm (standard)

↳ relative attenuation out water phantom



- Exponential attenuation (fixed E_γ) with thickness
- Interest: isodose α, → in a straight line
- dose depth → $\frac{1}{r^2}$ ⊛ attenuα phantom ⊕ scatt volum

⊕ Keilfilter attenuα

still: ↳ $D_0(z) \approx D_0 e^{-\mu' z}$ for $z > d_{max}$ (μ': effective atten. coeff)

$\forall x$, same μ'

↓

$D_{up}(z) = D_{up} e^{-\mu' z}$; $D_{low}(z) = D_{low} e^{-\mu' z}$

if Δz same effect than on central $\Rightarrow \frac{D_{up}}{D_0} = e^{\mu' \Delta z} = f$, $\frac{D_{low}}{D_0} = e^{-\mu' \Delta z} = \frac{1}{f}$

→ inclind due to Δ < lat profile / dose depth prof

⇒ exponential lat profile are needed for linear isodose!

↳ so linear wedge needed

- Reality: smooth borders, not homog., spectrally different as function of x (due to flattener filter)

depends also on E step

↳ $\mu'(x)$ → position dependent

↳ borders: lower E filling → higher $\mu'(E)$

μ' in phantom also (z), deeper → less E (more scatt) → μ' ↑

- Wedgefilter also affects E spectr, dose profiles (diagonal)

⇒ not theoretical but empirical construction / optimiza

↳ isodose not perfectly linear and smoother edges

- Large weight → only for restricted field sizes
- should be coded

⊖ worsens skin dose and profiles worse, specially if close patient

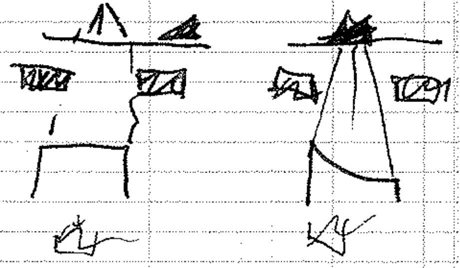
solutions / motorized wedge filters / dynamic

Motorized wedge filter

- integrated in nozzle, remote control, below dose monitor

most: single one with 60° isodose angle (rest with trick?)

- rotatable as collim. around central axis
- below DM → small backscatter, but ok, as external W.F.
- above DM → affects it, symmetry broken, sum signal affect.
  - ↳ correction factor in the control electronics
- $\alpha \neq 60°$ w/o wf; with; given ratio (time), auto calculation
- close to focus → more compact than external, more precision needed ⊿
  - ↳ less impact skin dose
  - ↳ change anyway E spectr.

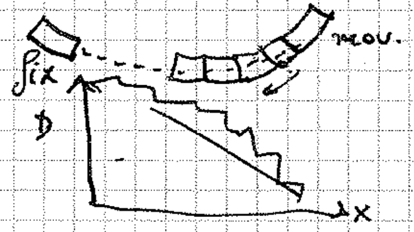


Dynamic wedge filter

(virtual w f) → no absorber

↳ dynamic adjust of 4 apertures of phot. coll. during irradiat.

- need movable apertures with overtravel (over field middle)



- time ratio auto calculated for α isodose
- $e^{-\mu z}$ does not apply here, independent of beam quality
- ⊕ less depend. dose depth prof from α, because E spectr not affected, just smth from scatter
  no extra material att., no contaminat. e^-, γ' ⇒ less skin dose
- complex shapes by moving the 4 apert. of γ coll
- ⊖ restricted field size, just 10 cm overtravel
  - ↳ need for external w filter for bigger
- ⊖ dosimetric monitoring, MU correction factors
  - ↳ w f factor, $D_{central}$ ↓, isodose depend on $\dot{D}_{power}$ and collim. speed
  - ⇒ need for accurate $\dot{D}$ tuning accel. (stable) + precise move

- can also be done with MLC
  - ↳ all together == dyn w f.
  - ↳ individual move → more complicated security, QA, dosimetry

---

Conformal → I not modulated, just maybe wedge filter

IMRT → pat-specific compensator (Blocs)
↘ motorised MLC < Step and Shoot / dynamic

LINAC: 3 – 5 Gy/min, Biologie not < 1Gy/min (reparation)

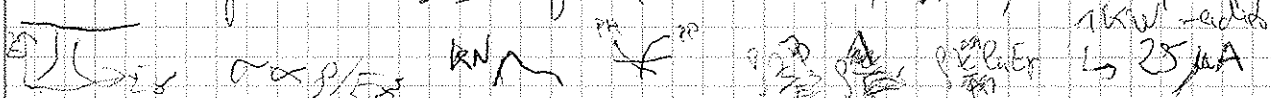
Why macro → too hot, alternativ: superconducting ELBE

~~Negative~~ [illegible]

---

not C230 for isot < E smaller / I higher (short-lived, $T_{1/2}$) → activ equil.

1W therapy
1kW radio nuclide
↳ 25 μA



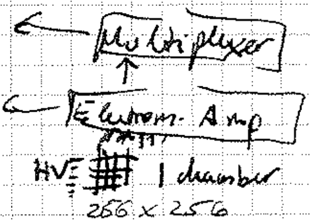
Portal Imaging Systems

- online control of irradia of γ, pat position, tumor shrink
- check OAR are spared
- useful for MLC, complex fields, ... as QA, independent
- shrinked field technique (boost smaller volume) → target must be accurate
- use bunch for imaging → X ray films (less sensitive, higher dose)
  ↳ store film in casette metal — sec. e^- (cGy sensit)
  \ previous CS/PP is shielded (no info) contrast

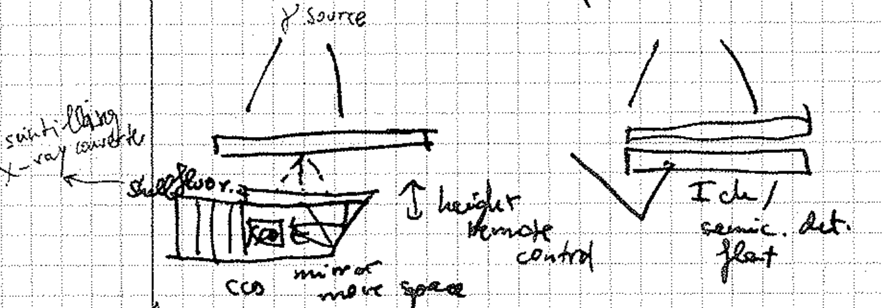
- alternative: Se films + laser scanner
- both

⊖ bad image quality, contrast

⊖ delay until analysis → not online



Solutions < fluorescent shell 45° over CCD camera
scintilling x-ray converter
matrix liquid I chamber / ~~flat~~ semicond. det. → M-Ω amplif to computer
↳ off-axis images easier, less space



cGy sensitivity for full image

filter

Cine-Mode

combine open slit, Δ image

compared to films.

⊕ compare with reference expected / simulated // previous
↳ define contours, Δ > Dcrit → interlock

- large faces
- CP dominates
- not for e^-

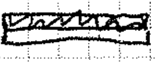
× Feedback to pat. positioning did not work

1) quantitative Δcrit difficult (respird, ...)
2) prompt correction → table oscillation → geometry even worse

$\boxed{3}$ multifield plans (spare OAR) → 3D move ampl. threshold
↳ not enough the precision single field, get 2D image ~~target~~ forget organs 3D
↳ not applicable during, but signal useful still as interlock

- New: independent X-ray panels pat. posit. on gantry,
  or even complete CT → allows 3D image → this doe allow pat. pos. correction but not online, just before
  ↳ but technical effort...

- coordinate/angle corrections after control CT > dcrit
  ↳ check TP
- replanning by geometry changes ⇒ affect isodose, MU, ...



metal plate
phoshor screen CsI segmented
or Gd_2O_2S
also liq I-cham

8.8 **Radiation safety issues ~~in~~ e^- LINAC**

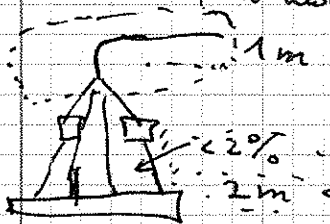
- protection < staff / popula / patients → respect dose limits
- beam on → closed ; off → überwachung , pregnant < 1 mSv

① **Construction**

- LINAC bunker → concrete walls + Baryte extra close to accel.
- neighbour rooms ≤ überw ; even windows, take care γ', e', n
- applicable to all E, types, ...
- high E → nuclear photoeff → n ⇒ door shielding boron/paraffin (↗ moderates, ↘ neutron capture)
- entrance → labyrinth, not focus seen (γ')
- doors: security interlocks + motion monitors ; not-aus switch

② **Apparatus**

- shielding protect patient (during irradiation) ← coll leaks transm. (chest nozzle) ; out of target regions ; contamind — γ', e', n (ph. mode) : transv overflow ; \ γ_b (foils, patient) → (e mode) skin dose : tail depth prof.
- n (n. photo) : activd patient, air, materials, nozzle
- $\dot{D}$ limits wrt applied (usable) to patient, central, ct. depth (and also γ' from patient even if perf shield)



1m < 0,5 % γ, 0,05 % n ; e^- → 2 cm ≤ 10 % out field

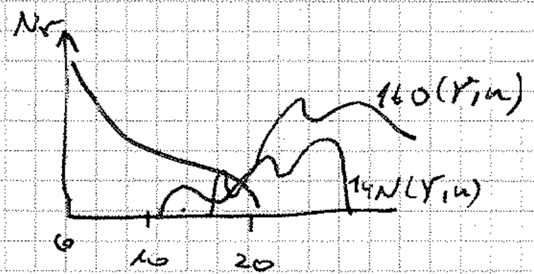
<2 %

2m < 0,1 % γ, n 0,02 %

Material activa

- E_γ over Knuc threshold 8-10 MeV
- 5-6 μSv/h , 0,5 m nozzle
- 2,5 μSv/h patient
- air activa → ventilator 10×/h
- problem : impure material (alloy) → neutron capture → long living isotopes

$\left\{ \begin{array}{l} ^{11}C^* \quad \beta^+ \quad 20\,\text{min} \\ ^{13}N^* \\ ^{15}O^* \\ ^{14}O^* \\ ^{26}Al^* \quad 6\,s \\ ^{62}Cu^* \\ ^{207}Pb^* \quad \beta^- \end{array} \right.$ ~~207Pb~~ + photoneutrons



γ cam dose < Δx / activ =

C fragments lower Z, $\frac{dE}{dx}$ → longer range

→ modified ; no coll

HV no extra paralle

Decay 6 MeV 2 0^+ a 0^+ no via γ ΔL = 0, via EC but low cross section (2nd level)

CT → lin att coeff μ

SFUD

negative <
- stripping extraction 100% eff ; any radius thin foil ⟷ change of curvatu out of field (Al_2O_3 / C)
- CE [illegible] concentration
- distance tracks, bunch charge effects ; size – max E
- better negative high intensities ~~low~~ E

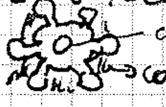
8.9. Cyberknife (Accuray)

- avoid deflect. magn, ESS, mov. apert, bi-mode, E steps of e LINAC
  ↳ spare space, weight

⇒ light, compact ⇒ industry robot (1,2 t)

e.g Cyberknife: 6MeV e LINAC + IR (6 axes, 0,2 mm precision)
(8)
- 160kg nozzle containing: target Brems W cooled / dose monitor / fixed apertures / 2 Xray / flat panels
  1m laser
- 3D Video cameras, marker patient
  ↳ for motion compensa

- Standing wave, 9,3 GHz (3,2cm) → 3 times smaller
- RF source: magnetron



resonating cavities

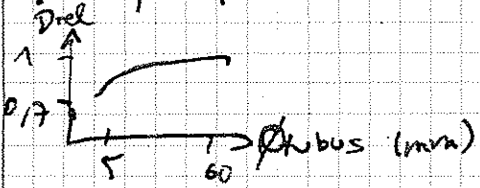
RF antenna not enough GHz

- dose monitor:
  sandwich closed I-chambers (Ar, air), 400V
  16mm × 12mm Polymid, gold
  ↘ with symmetry check and interlock

~~klystron~~ Ekin (e) ↳ RF source (second one)

- collimator: ∅5 – 60mm × 10cm
  (12 circular tubus)
  ↳ no need for ~~flatness~~ filter
- hole convergent to minimize lat penumbra
- lat profiles Gaussian if small, not flat
  but good fall-off 80% - 20% 3-4 mm

- focus - skin distance 80 cm - (65 cm - 100cm)
- output factor (rel. $\dot{D}$) ~ 30% varia with field size



- $\dot{D}$ = 4 Gy/min @ 80cm
- dose depth profile 6 MeV
- no gantry → no isocentric radia needed → custom, allows more complex targets
  .. stereotactic irradia
- room-fixed stereo X-ray system high accuracy + 2 Si flat panels
  ↳ for check patient positioning + also Portal Imaging
- 3D video for patient marker
- easier motion tracking feedback due to robot (2 steps)

1) X-ray flat panels compared to 3D-CT, 3-4 itera with 5-axes table (2min). During irradia: 100 spots each measured X-rays images
   ↳ adiabatic shifts transferred to robot live (extra 10mSv) negligible
2) Video (IR) supported respira tracking, marker ...emitter breast red light
   before irradia → 1-2 min track, 5-6 Xray Images for 3D correla
   (learning phase)
   During irradia → 33Hz video → robot auto corrects

⇒ avoids moving patient oscilla + avoids just 2D w. Portal Imaging

9 Circular accelerators

- RF alternating V accel charged particles (e^-, ions)
- magnetic fields needed $\vec{B}$.

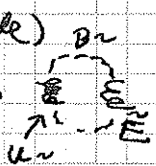
types
- B(r)
- B(t)
- ν; $\nu(t)$
- accel princip

- several laps of accelerꭤ
  ↳ circles / spiral / ⊖ ✻

Accel	ν	Macrop	B	Way	Part
Betatron	50Hz	✓	B(t)	○	e^-
Cyclotron	10-30 MHz		B(~)	◎	p, d
Isochroncycl	10-100 MHz		B(r)	◎	
Synchrocycl	$\nu(t)$ ↓	✓	B	◎	
Microtron	2-3 GHz		B	◎	e^-
Synchrotron	100MHz	✓	B(t)	○	e^-
	$\nu(t)$	✓	B(t)	○	p, I
Rhodotron	100-200 MHz		B(r)	✻	e^-

Betatron (1940) Kerst, not used any more

- e^- accelerꭤ based on induction law (transformator principle)
  just relativ.
- low RF ~ 50-60 Hz (usual volt.)
  ↳ two inductors

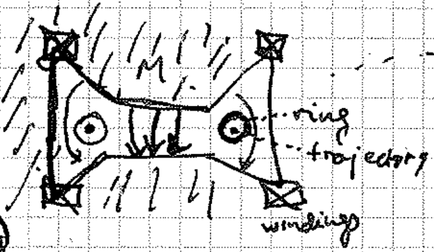


- replace second ind. with glas / cheramic ring
  ↳ free e^- are accelerated, 1 million laps
  ↳ compensate F_{centr} with $B_\perp(t)$ to not collide with outer ring walls
  ↳ constant radius

over lap … for offset ring

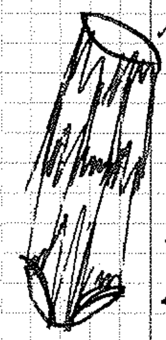
$$B_f(\cancel{t}) = \frac{1}{2}\overline{B_b}(t) + B_0$$ Betatron condition (Wideröe)

or $dB_f/dt = \frac{1}{2}\, dB_b/dt$

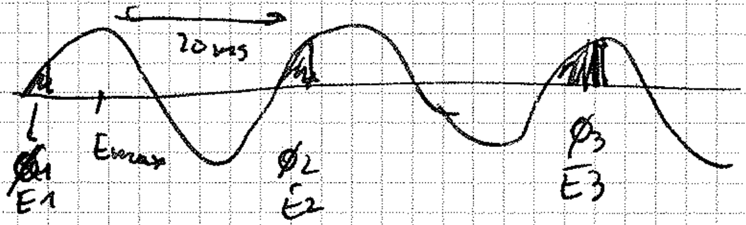


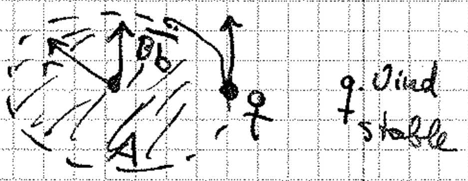
→ if B_f as B_b reused, only 1st quarter period from accelerꭤ to extraction … 1-5 ms inside

- 1 µA, each 50Hz, … 1-5 µs width
- $v \gtrsim c$ from beginning e^- emitted cath wire
- up to 40 MeV clinic; 300 MeV research



- less accurate ΔE, … than e^- LINAC, dependence ring orientꭤ
- circular e^-: Srad loss
- not anymore





$$\frac{d\vec{p}}{dt} = q\cdot\vec{E} \Leftrightarrow$$

$$U_{ind} = \frac{d\overline{B_b}}{dt}A = 2\pi r E$$

$$\frac{dp_z}{dt} \leftarrow \frac{mv^2}{r} = q\cdot B_f\cdot r$$

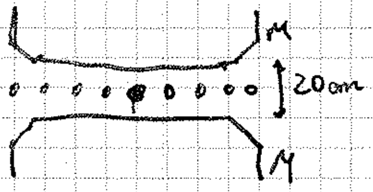
Cyclotrons EO Lawrence 1929 (1931)

- RF accel for p, d, α, ; periodic, on D-hollow electrodes
  - production radionuclides (short lived) for nucl. med. specially positron emitter
  - neutron production (nuclear reactions)
  - material sterilisα / polymerizα
  - research

- Coulomb barrier → threshold ≈ 20-30 MeV ⇒ need for relativistic cycl. for nucl reac (radionucl)
- p best for accelerα $\frac{q}{m}$ ratio $\begin{pmatrix} P_{rad}\downarrow \\ D(p)\downarrow \end{pmatrix}$ ⎯⋀ ; RBE = 1,1

Principle

- two halfring hollow electrodes (DEE)  saw ⊗ homog. magnet field
- each lap → increasing ϑ, r • B constant in time
- r → R : deflector magnet for extraction / field shielding



V ~ 100-200 kV (not higher / ↯)

$q v B = \frac{m v^2}{r}$ → $\boxed{r = \frac{p}{qB}}$ cyclotron resonance condition ↓

$\boxed{\omega = \frac{qB}{m}}$ Phase stability : $\omega_{RF} = \omega_T$

$\omega(m)$ → if not relativistic ok, $\beta < 0{,}15$ $\omega \propto \frac{q}{m}$

e^- already at 6 keV, and $\omega\uparrow$, and P_{rad}, but $B\downarrow$ $\omega \neq \omega(v)$ non-relat.

$\boxed{E_{max} = \frac{(qBr_{max})^2}{2m_0} = \frac{mv^2}{2}}$ $B_{max} = \begin{cases} 1{,}5\,T \\ 5\,T \end{cases}$

- for phase stability $u(\varphi) < U_{max}$ → $\Delta E_{typ} = 50\,keV$, n ≈ 100 laps ≈ 1,2 km

$\boxed{r_n = \frac{1}{qB}\sqrt{2 m_0 n \Delta E}}$ $\propto \sqrt{n}$  out : closer

$E = \gamma m_0$

$p = \gamma\beta m_0$

$E_{kin} = (\gamma - 1) m_0$

$\beta = 0{,}15$

$n\omega^2 r = qvB$

⇒ ver/hor stabilizα ! DEEs

- 1 mA, pulse γ, up to 10 MeV p, 60 MeV α

Vertical stability

- oscillα around Soll-trajectory, if too high, collide wall

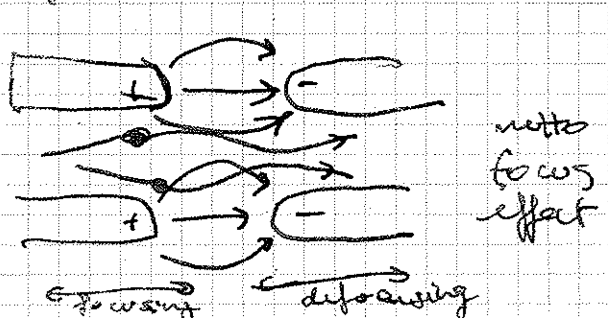
↳ avoid with magnet rounding, focusing F_L

↳ affects resonance condition → diminish slightly & increase ⟶ middle outer laps

⊕ passage DEEs E field inhomogen, focus + defocus effect

but netto focusing vertically ⋮ more time here (because winning still v, and E bigger left)

if relativistic (v = c = ct) → no effect (= times, and E no eff)



Relativistic cyclotrons

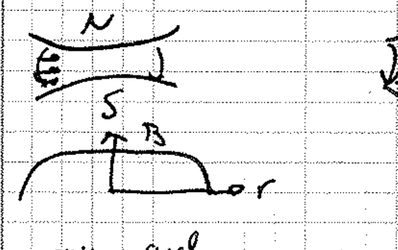
12

- W_{HF} constant → only in phase if $\omega \propto \frac{B}{m}$ ct ⇒ modify cycl. principle
- relativistic m↑, ω_r↓ → lost from bunch

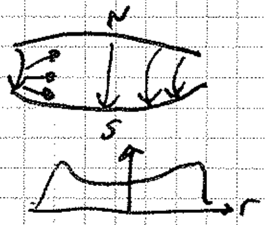
Solutions ∠ $\nu(t)$↓ → Synchrocyclotron, pulsed (~~single~~) macropulse mode
↳ << I, up to [illegible]
↳ ω_{min} → deflect/extraction

$B(r)$↑ → Isochroncyclotron
↳ closer magnets
↳ but defocuses (axial), traj. unstable
⇓
alternate shapes per lap with high / low inductivity
Sector magnets azimuthal change (straight / spiral shape)
↳ boundary has focusing effect that compensates other one

$\omega = \frac{q B(r)}{\frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}}$



norm. cycl.

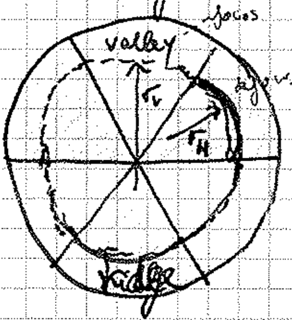


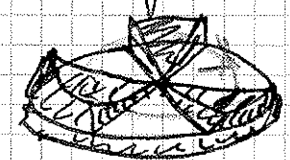
isoch ty

→ curvature radius varies/sector

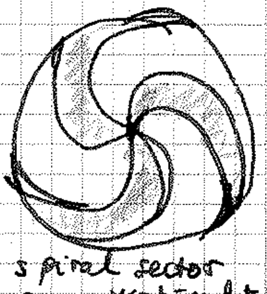
⇒ not so high E as with synchrocycl, but higher I (~μA)

both: higher costs (magnets)



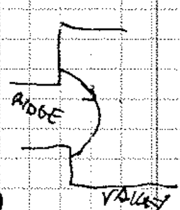


simple sector
isochroncyclo.
60°



spiral sector
for vertical + radial focusing

$B(r) = B_0 \left(1 + \frac{1}{2}\left(\frac{qBr}{mc}\right)^2\right)$



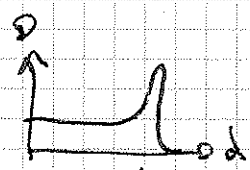
Δ

- iron joke magnets high B → large mass, but shape forming easy, homogen.
  but: just up to 2T (saturd)
- if larger: closer to DEEs, but vertical confine more difficult $=^{s}$
  ↳ instead: superconducting magnets without iron
  - justage with winding (difficult) → price, technique
  - allow B(r) without constraining vertical space

➡ for radionuclide
industry rad. source
prot therapy

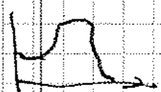
if 2 dees: 4 ΔE × lap

Cyclotrons proton therapy



Bragg curve
↳ high scal, LET

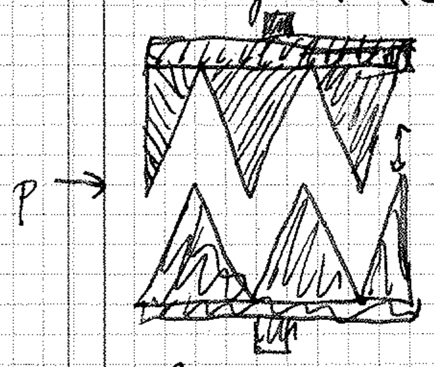
- 250 MeV → isochron cyclotron
- RBE = 1,1
- Spread out Bragg Peak (from largest E to lowest) to homog/flat
  ∴ most dose (50%)
  ↳ layer change: ~s



- DS (spread)
- Pencil beam 2 Gy/min, spot peak 10 Gy/s
  ↳ also multi-field for sparing skin
- ocular tumours, single field, up to 15 Gy/fraction

- medical cyclotrons, fixed E (practical reasons)

↳ degrader (C), graphite wedges, fast motor



... robust against vertical bunch drifts

⟹ angle spread → ∝ acceptance : transmission loss

energy spread

E↓ → changes Bragg curve (blurs)

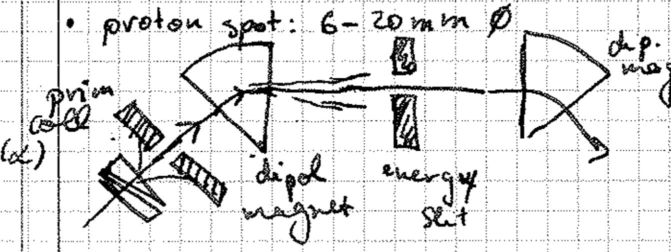
Scatt loss but D not that near BP

(∝ E↓)

- ≙ e⁻ LINAC: combine slit / sector magnets ⟹ magnet spectrometer

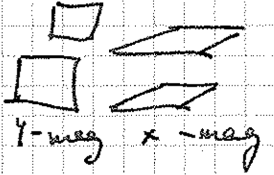
↳ reject bad ∝, E

- proton spot: 6–20 mm Ø



- sweeper magnets

$30 \times 40\ cm^2$ (y, x)



→ IMPT possible:

- gantries – 380°, patient table 3D (stereotactic)
- Munich 250 MeV isochron cyclo (supercond)
- nozzle: x-y sweeping magnets, conus tubus, monitor ch., 2 flat panel
- FBTR → no scanning → Tantalum, low Z scatt foils

x-ray tubes in gantry

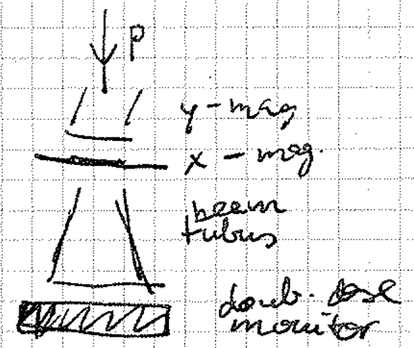
↗ CT plan

$= qBr$

m

$= qBr$

$= \frac{p}{qB}$



C230 isochr cycl	S2C2 synchr cycl
Ø ~ 4m	Ø 2.3 m
210 t	50 t
$\bar{B}$ (1,74 – 2.2 T); Ridges 3T Valleys 1T	superc. 5 T
55 – 150 kV dee	14 kV dee
106 MHz	90 - 60 MHz (-33%)
Quasicont 9.4 ns (2ns)	Pulsed 1 kHz (30µs width); 16,6 ns (2ns)
300 nA	150 nA
230 MeV (0.6 MeV @ 2σ)	230 MeV (2.5 MeV @ 2σ)

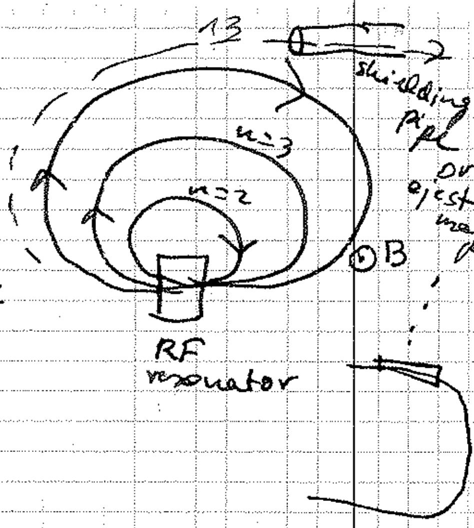
9.4 **Microtron** (Veksler 45) - Circular

- RF accel for relat. e^-
- single cavity resonator (~3 GHz)
- B constant, homogen, circular room
- each lap: ΔE so that new $t_u = n \cdot T_{RF}$; $\omega_T = \omega_{RF}$ (Microtron resonance condition)

$t_u = \frac{2\pi E}{qBc^2}$ (e^- are relat.)

1st condition: $t_u = n \cdot T_{RF}$ ← constant

2nd " $n = 2, 3, \ldots$ ($n > 1$)



- Ø 1-2 m ; 22 MeV
- high vacuum
- very low ΔE (resonance) → easy to transport

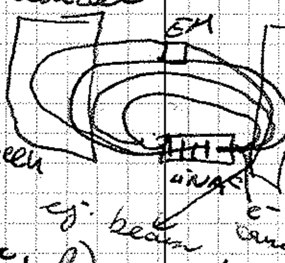
↳ thus racetrack variant in 2 half magnets, no mag. inbetween

↳ larger linac section, also quadrupole

↳ up to 100 MeV, ..

to ejection magnet w motor to track

To gantry, medical



$t_{u,l} = \frac{2(\pi r + l)}{v} = n \cdot \frac{1}{\nu_{HF}}$

↳ adapt, B, r

⊕ low ΔE, good depth prof

⊖ high magnet cost, vacuum volume → not widespread

⊕ usable several rooms

× sometimes as pre accel of synchrotr.

9.5 **Synchrotrons**

$qvB = \frac{mv^2}{r}$

$p = qBr$

$r = \frac{p}{qB}$

- high E, most for p, e^-, circular accel with mag. just on track

↳ storing rings

↳ synchrotron radia (by product)

$r = \frac{E}{qcB} = 3{,}33 \cdot \frac{E/GeV}{B/T}$ [m]

- iron yoke → 2 T
- supercond → 10 T

} 10 GeV, 1,5 T: $r \to 22$ m

→ Veksler 1945 McMillan ⇒ magnets not whole area, just along track

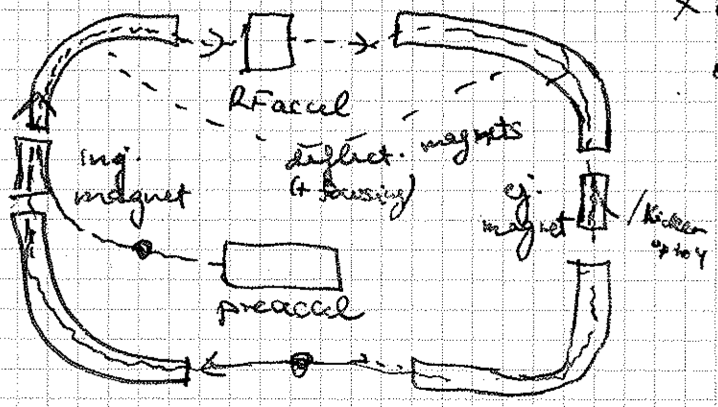
⇓ much smaller

× between turns: straight, LINAC sections

× need for constant r for increasing E → tune B simultan. (sync)

↳ needs macro pulse mode

× and condition $t_u = T_{RF}$



- e^- : $v = c$

$\nu_T = 477 \text{ MHz} / r$ [m]

↑ constant

just $B(t)$

+ 1,5 keV / lap (3 kV)

$r = 5$ m → 10 MHz

10^{-2} s until until 150 MeV

E_{max} → 10 GeV

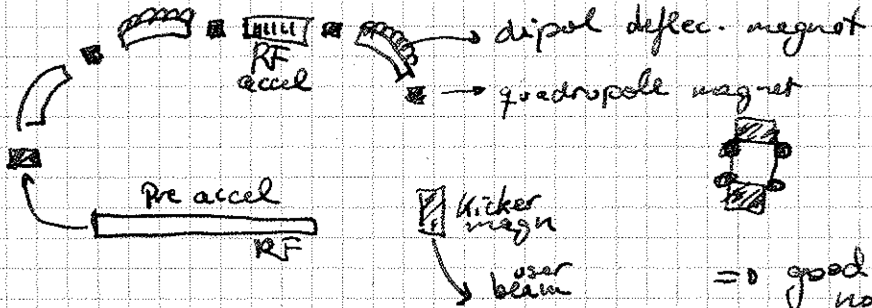
later Prad loss

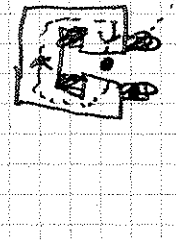
- p ⇒ $v \to c$ at 10 GeV, not before
  - ↳ so need to increase ν_{RF} with E
  - ↳ $\nu_{RF}(t)\uparrow$ and $B(t)$
- up to 1 TeV
- pre-accel needed ($\nu, B \to 0$ not poss) : microtrons / LINAC
  low thresh

× inject/eject with fast switch magnets (kicker magnets) ~μs

1 Sp. focusing
× high number of laps → require spatial / timing focus
intensity yield ↲ ↳ low ΔE, phase focus.

- transversal oscill → risk of outer wall collision, lost from bunch
  - ↳ focusing magnets, strong (multipole)
    - ↳ separated → modern
    - ↳ combined
    function -- with deflection (dip+qp together) winding





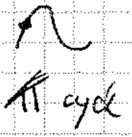
⇒ good as storage ring, no loss

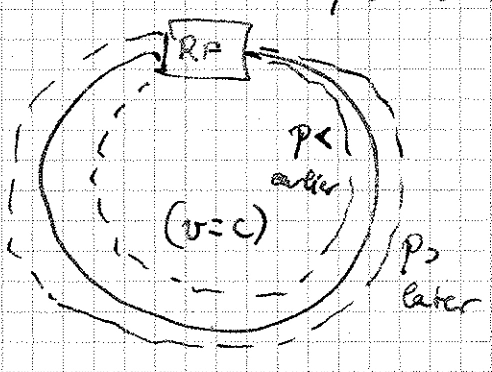
2 Phase focusing (timing / E)

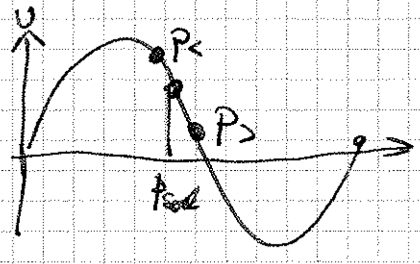
↳ spatial/timing compactness for RF accel

↳ $U < U_{max}$, but $+\pi/2$!

- out of phase
  - ↗ ↑ faster (v=c) : larger radius, later : lower U : φ↓
  - ↘ p↓ : smaller " , earlier : higher U : φ↑







⇒ automatic timing focusing

↳ synchrotron oscillation, phase oscill. (all circ. acceler.)

compact:
↳ even p, $\bar{p}$ opposite directions same time ⇄
and then collided

$$P_{rad} \begin{cases} \parallel & (10^{-14}) \\ \perp & \end{cases} \propto \frac{Z^2}{M^4}\frac{E^4}{R^2}$$

→ avoid loss → large R

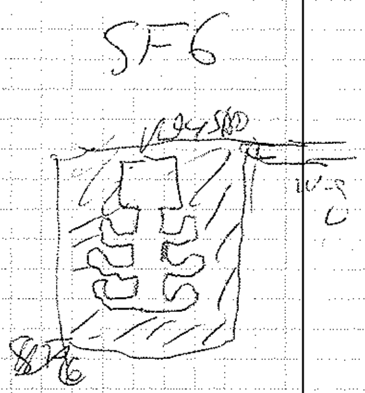
→ gain synch rad → low R

$\varphi = \frac{m_0c^2}{E_{e^-}}$ wiggler, undulator

Rhodotron (1989 Pottier), e^-

- vacuum chamber 1-3m
- coaxial cavity resonator RF 107-215 MHz
- radial electrical alternating field between outer wall (Cu) and inner cylinder (metal) ⫫ → holes for passag
- circular accel for e^-
  - ↳ 1 MeV / lap
- e^- canon (40 keV), each RF period
- out of cavity → in home. adjustable magnets mirror track, RF: π swit.
  - ↳ rosette trajectory (rhodos = rose)
- 10 MeV / 10 "laps", not more Kph
- 3,5 - 100 mA, continuous (still micro pulse RF)
- low ΔE, → easy transport / no loss

× sterilisa, ..., industry, polymerisa, color change



$$\vec{F} = q \cdot \vec{E}$$

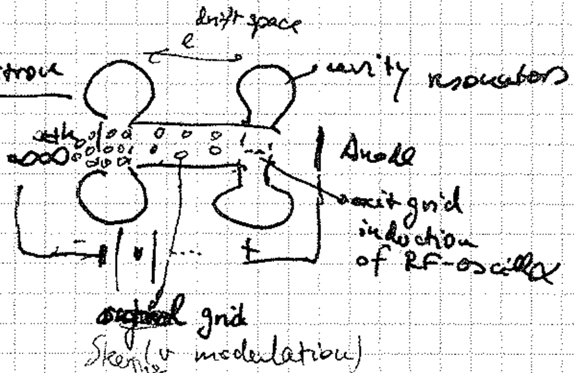
$$\vec{F} = q\, \vec{v} \times \vec{B}$$

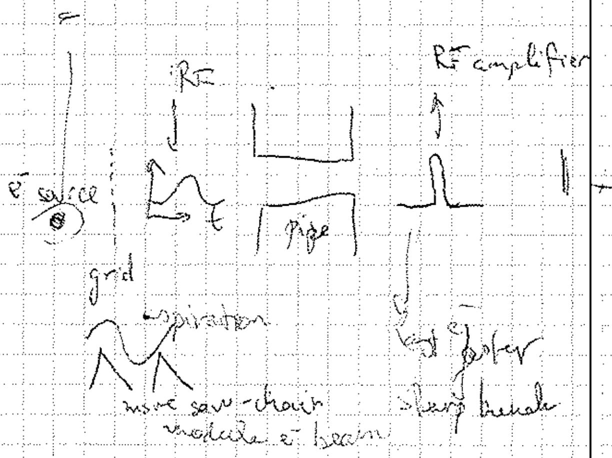
$$B = I/2\pi r$$

$$V = Ed$$

$$B\rho = \frac{P}{q} = \frac{\gamma m_0 v}{q}$$ magnetic rigidity

Klystron





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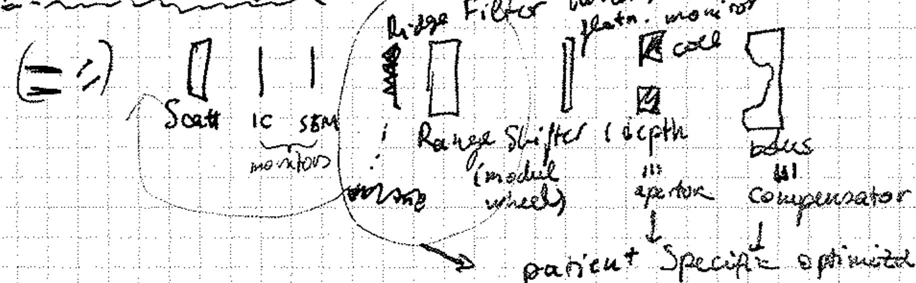
parallel-to-point: magnet quadrupole $L = \sqrt{f_2 (f_1 - f_2)}$

Bethe-Block $\left(\frac{dE}{dx}\right)_{col} = S_{col} \propto \frac{\overset{\text{target}}{\rho Z}}{A \beta^2} z^2$

$$R_2(E_k^2) = \frac{M_2}{M_1} \frac{z_1^2}{z_2^2} R_1\left(E_k^2 \frac{M_1}{M_2}\right)$$

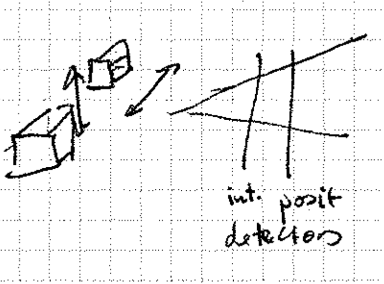
$$\beta_I = \beta_p \rightarrow R_I = \frac{A_I}{z_I^2} R_p$$

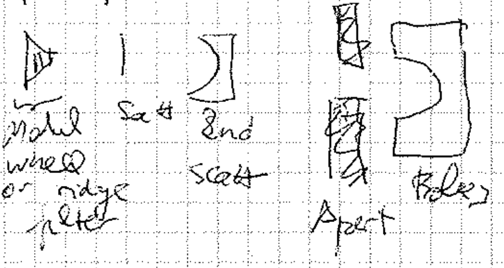
PT – Passive scatt



Active

IMPT





I- chamber Impuls – ionized ch. : Q

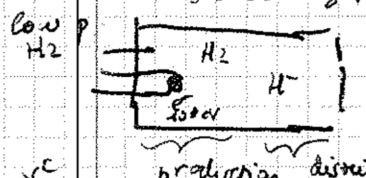
$Q = \int I\,dt$ → measure charge $-|\,\cdot\, \rightarrow|+$

current ch measure I

GM-Z τ

Multicusp ion source (external) → easier maintaining, vacuum

source negative ions



magnetic filter

for separate slow from fast e⁻, get plasma, avoid recombination

C 25μm foil

→ e^- stripper H^+

$\vec{B}$ curv. change

→ C.E. Hill CERN

$\rho_{negions} \gg \rho_{exp}$

in low pressure H2 discharges

	$T_{1/2}$/min			CNOF NO,00 BCNNe
^{11}C	20	$^{14}N(p,\alpha)$	$^{10}B(d,n)$	
^{13}N	10	$^{16}O(p,\alpha)$	$^{12}C(d,n)$	
^{15}O	2	$^{14}N(d,n)$	$^{15}N(p,n)$	
^{18}F	110	$^{18}O(p,n)$	$^{20}Ne(d,\alpha)$	

β^+ emitters

Thick target yield, N_{prod}, $d \to \infty$, [illegible] N_0 $\frac{dN_p}{dx}$

$\Sigma = \sigma n$

$$y = \frac{A}{Q} = \frac{\lambda N_p}{Q}$$

$$dN_p = N(x)\,\Sigma(x)\,dx \rightarrow N_p = -\int \frac{N\Sigma}{S}dE \rightarrow N(E) = N_0\, e^{\int \frac{\Sigma\, dE}{S(E)}}$$

S – stopping power

$$\frac{dN_p}{dt} = \frac{yI}{\lambda} \rightarrow A(t) = \frac{dN_p}{dt}(1-e^{-\lambda t}) = \frac{yI}{\lambda}(1-e^{-\lambda t})$$

$y(d) = y(E_0) - y(E_1)$

$d = R(E_0) - R(E_1)$

Y_i → GBq/C

13

Krieger

Radionuclide generation

nucl med = use open rad. subst localis / funct diagn. ^{11}C, ^{18}F

methods:

- use of fragments from neutron-induced nuclear reactions
- β^- neutron activation of stable isotopes for β^- source (neutron capture)
- β^+ radiators through nucleer reactions, in compact cyclotrons / charged part with stable isot.
- short-lived: radionuclide generator system

× radioactive medicine $<$ therapy / diagnostics

• β^-: neutron excess nuclei, due to: → Bethe Weizsäcker, low Z, not that n more (SEMF)

↳ fragmentation of heavy nuclei in nuclear reactors n-induced … asymmetric spallat ↳ product radioch. separa

or

↳ neutron capture of thermal n

• β^+: proton excess nuclei, due to:

↳ charged particle shot on stable (more p than n transferred)

(high currents: compact cyclotrons)

• Radionuclide generators (e.g. Mo – Tc)

- parent nuclide with long τ for transport, storeing
- daughter " (s) → shorter τ and prefer. just γ source (less probl if contam + minim pat.

↳ usually excited isomere states of stable one

↳ relaxed state: long τ or stable, to minimize patient exposition

• radionuclides σ_{prod}, contaminated with parent

↳ radiochemical separd for pure daughter → carrier (freedom) absence

AND separate stable ones (would bias quant. test) imaging

Specific activity

• choose based not only on A, but $a = A/m$ (compactness) mass-specific activity

↳ depends on pureness, chemical conf., Z, T source, fluence (n), σ_{prod}

• N radioact. ele∅: $a_{th} = \frac{\lambda N}{m} = \frac{\lambda N_A m/M}{m} = \frac{\lambda N_A}{m} = \frac{\ln 2}{T_{1/2}} \frac{N_A}{M} \propto \frac{1}{T_{1/2}}$

$a_{techn} < a_{theor}$ (not pure, crystal, alloy)

• short-lived better for high a — σ_{prod} cc, transport, storing → for impure short-lived eliminad; T_{irrad} → …years; ^{137}Cs ⟶ ^{134}Cs 2y no chem.

× ^{192}Ir, ^{60}Co → cheaper (nucl. reactor)

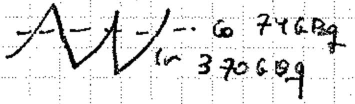
→ higher a

→ higher $\dot{D}$

→ larger Z

→ less attenud

} equal irradid times



Neutron-induced fragmentd

• neutron excess nuclei (for getting rich) → fragment actinides (^{235}U) with thermal n 2:3

↳ separate radioactive ones chemically

• ^{131}I (thyroid); ^{137}Cs; ^{99}Mo; ^{90}Sr

~~↳ there to minder short-lived~~

Neutron activd

• neutron-rich nuclei (β^-): targets with neutron irrad.

↳ neutron capture $<$ n, γ … β^- / n, p … β^-; (β^+), (EC)

• low n E enough, no Coul. barrier (thermal n)

- higher σ → higher a_{techn} (Ir, Co)
- low σ_{nr} → 99 Mo → better fragmentd method
- Neutron sources: – nuclear reactors (thermal target @ field)
  – neutron generators (charged → target → fast n)
- capture activd → low daughter concentrd (10^{-6})
  - ↳ not carrier-free
  - ↳ fast β^- → then chemic. separd
  - ↳ or backscatter nucleus (Szilard–Chalmers effect 1934)

$E_K = E_\gamma$, $p_K = p_\gamma$; $E_K = E_\gamma^2/2M$ → 103eV → gets ionized (escape e^-) + moves

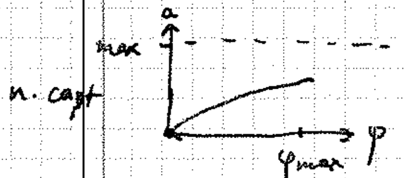
__Activity ratio__

$$\frac{dN_p}{dt} = -\sigma_n \varphi N_p(t) \qquad \frac{dN_d}{dt} = \sigma_n \varphi N_p(t) - \lambda_d N_d(t) \qquad \lambda_p = \varphi\sigma_n$$

$$N_p \sim A e^{-\lambda_p t} \qquad N_d \sim B e^{-\lambda_p t} + C e^{-\lambda_d t}$$

$$N_p(t) = N_p(0) \cdot e^{-\varphi \sigma_n t} \qquad N_d(t) = N_p(0) \frac{\varphi \sigma_n}{\lambda_d - \varphi\sigma_n} \cdot \left(e^{-\varphi\sigma_n t} - e^{-\lambda_d t}\right)$$

- high λ_p : $N_d \sim (e^{-\lambda_d t})$ ↗ saturd 4z
- low λ_p : $N_d \sim (1 - e^{-\lambda_d t})$ ↘



→ not good, far away

Mo-98 (p) → better fragmentd despite radioch. problems

- probes in Alu pots or quartz in commercial / research reactors
- short-lived → fast transport tubes
- long-lived → within fuel reactor hole

× graphite blocks for moderd and probe holders

× water reactors → fishing

__β^+ generation__ (positron)

- get proton-rich nuclei → shot + charge to nuclei $Z \to Z+1$
  ↳ β^+ / EC isotopes

$E >$ Coul barrier ~ some MeV (elasd transmutd)

Energy threshold : $\propto \frac{zZ}{r}$

$R \propto A^{1/3}$

$r_{min} = r_0 \cdot \left(A_{proj}^{1/3} + A_{targ}^{1/3}\right)$ r_0 (proton radius) : 1,4 fm

$$E_{th} \sim 1\,\text{MeV} \frac{zZ}{A_p^{1/3} + A_{tar}^{1/3}} \ll 100\,\text{MeV}$$

× easy to achieve with p, d, ^3He, α not relat. compact cyclotrons
↳ shot into target for nucl reaction

× most: short-lived → cyclo close to nucl. medicine institute
high costs (accel, lab) → few places + transport

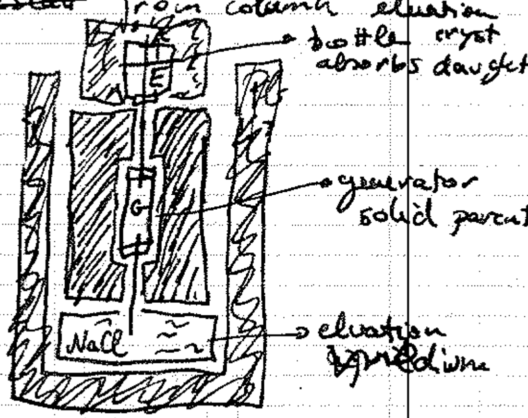
13.5 Radionuclide generators for nuclear medicine

- always needed, when too short-lived to transport

↳ instead parent-daughter equilibrium of long τ_p parent

↳ decay parent to "isomer" daughter states of sufficient τ_d^* for in situ applica
metastable

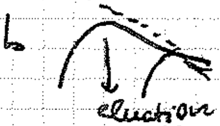
- contain parent in column pot
- daughter has to be chem. lighter to escape ~~backscat~~ by recoil from column elution
↳ diluted in NaCl (salt water) physiol.
electroaffinity

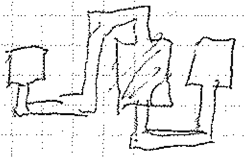


$$A_0(t) = \lambda_0 N_0(0) \cdot e^{-\lambda_0 t}$$
$A_0(0)$

$$A_1(t) = A_0(t) \cdot p \cdot \frac{\lambda_1}{\lambda_1 - \lambda_0} \cdot (1 - e^{-(\lambda_1 - \lambda_0) t})$$

p: branching ratio daughter





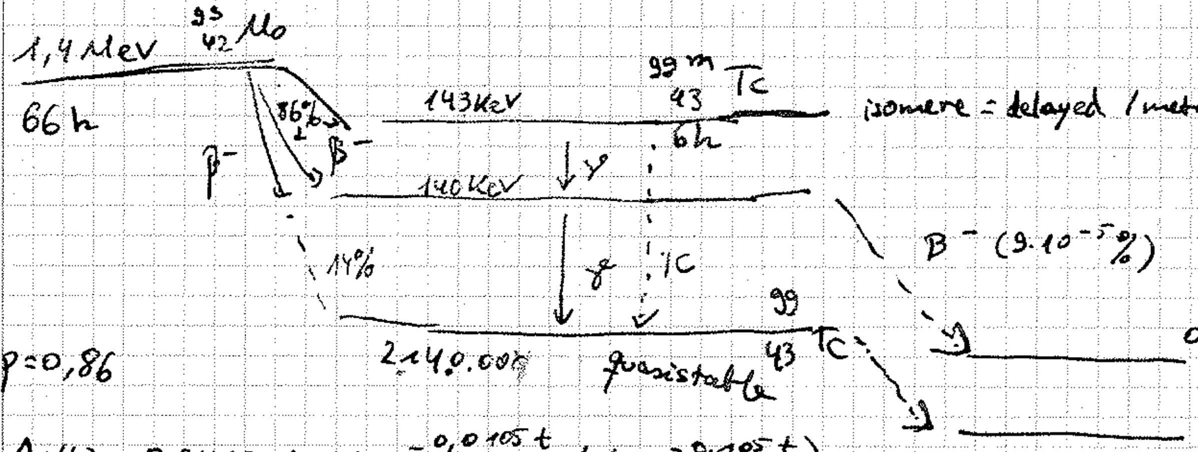
- eluate each x hours
- new ~~the~~ generator each week

most important: ^{99m}Tc → pure γ 140 keV (^{99}Tc 214.000 y), no β signif.
↳ γ-camera

Mo-Tc generator

fission moly ^{235}U + n

- radioactive spallation ^{99}Mo at carrier matrix $AlMoO_4^{2-}$ aluminium molybdat
- β^- + recoil as TcO_4^- w ^{99m}Tc free move, water dilluteable (salt)
pertechnat ... Na^+
↳ easy to eluate (wash with solvent)



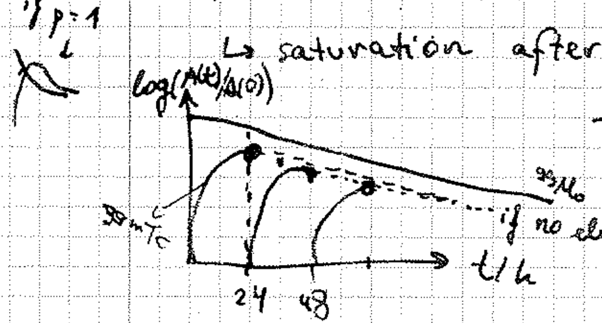
isomere = delayed / metastable

p = 0,86

$$A_1(t) = 0,9463\, A_0(0)\, e^{-0,0105 t}\, (1 - e^{-0,105 t}) \quad t/h$$

if p = 1

↳ saturation after 24 h, waiting more: decreases N_d | exp. w λ_p
↳ 4 half lives
→ elution each 24 h



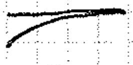
if no elux .. (slightly over ● sat-point

= milked cow

- thick lead shielding
- max : 37 GBq
- ^{99m}Tc: pertechnat ⏤ radiochemical marking
- eliminate Mo → Mo-Durchbruch test pureness + sterility (microbe)
too bad patient radio (β) + pyrogen free of elutions

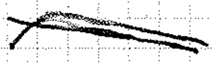
λ_p, λ_d $T_p < T_d$

- No equilibrium ~~$\lambda_p < \lambda_d$~~ $\lambda_p > \lambda_d$
- Secular " ~~$\lambda_p \gg \lambda_d$~~ $\lambda_p \ll \lambda_d$ 6 $t_{1/2}$



Ra^{226}, Rn^{222}

- Transient " ~~$\lambda_p > \lambda_d$~~ $\lambda_p < \lambda_d$ 4 $t_{1/2}$



$^{99}Mo, {}^{99m}Tc$

Further generators

- Thorium cow ^{232}Th $1{,}405 \cdot 10^{10}\,y \xrightarrow{\alpha,\beta} {}^{220}Rn$ (noble gas)
  ↳ E field Rn $\to {}^{216}Po$, ${}^{212}Pb$ sec. eq. → constant $A_d(t)$

  $${}^{220}_{86}Rn^{*}_{134} \rightarrow {}^{216}_{84}Po^{*}_{132} + \alpha + E \quad \overset{t_{1/2}}{(55{,}6\,s)}$$
  (p[illegible])
  $$\hookrightarrow {}^{212}_{82}Pb_{130} + \alpha + E \quad (0{,}15\,s)$$

- Zinn – Indium :
  $${}^{113}_{50}Sn^{*}_{63} + e^- \rightarrow {}^{113}_{49}In^{*}_{64} + \nu + E \quad (115{,}1\,d)$$
  $${}^{113m}_{49}In^{*}_{64} \rightarrow {}^{113}_{49}In_{64} + \gamma \quad (1{,}65\,h)$$
  → scintigraphy

- Tellurium – Iodine
  $${}^{132}_{52}Te^{*}_{80} \rightarrow {}^{132}_{53}I^{*}_{79} + \beta^- + \bar{\nu} + E \quad (78\,h)$$
  $${}^{132}_{53}I^{*}_{79} \rightarrow {}^{132}_{54}Xe_{78} + \beta^- + \bar{\nu} + E \quad (2{,}30\,h)$$

- Hg/Au ; Rb/Kr → not practical, replaced by Tc

- ~~[illegible]~~ : long $\underset{30y}{\tau_p}$, short $\underset{2{,}6\,min}{\tau_d}$ ... $E_{\gamma} = 662\,keV$ calibr.
  $${}^{137}_{55}Cs^{*}_{82} \rightarrow {}^{137}_{56}Ba^{*}_{81} + \beta^- + \bar{\nu} + E$$
  $$\hookrightarrow {}^{137}_{56}Ba_{81} + \gamma + E$$

- Hg – Au : EC 50% Au^*, 261 keV heart scintigraphy
  $${}^{195}_{80}Hg^{*}_{115} + e^- \rightarrow {}^{195}_{79}Au^{*}_{116} + \nu + E \quad (41{,}6\,h)$$
  $$\hookrightarrow {}^{195}_{79}Au^{*}_{116} + \gamma \quad (30{,}5\,s)$$
  $$+e^- \hookrightarrow {}^{195}_{78}Pt_{117} + \nu + E \quad (183\,d)$$

- Rb – Kr : lung scintigraphy
  $${}^{81}_{37}Rb^{*}_{44} \rightarrow {}^{81m}_{36}Kr^{*}_{45} + \beta^+ + \nu + E \quad (4{,}6\,h)$$
  $${}^{81m}_{36}Kr^{*}_{45} \rightarrow {}^{81}_{36}Kr^{*}_{45} + \gamma \quad (13{,}6\,h)$$

- Sr – Rb :
  $${}^{82}_{38}Sr^{*}_{44} \rightarrow {}^{82m}_{37}Rb^{*}_{45} + \beta^+ + \nu + E \quad (25{,}34\,d)$$
  $${}^{82}_{37}Rb^{*}_{45} \rightarrow {}^{82}_{37}Rb_{45} + \gamma \quad (776\,keV;\ 1{,}27\,m)$$
  $${}^{82}_{37}Rb^{*}_{45} \rightarrow {}^{82m}_{36}Kr_{46} + \beta^+ + \nu + E \quad (6{,}3\,h)$$

$^{68}Ge/{}^{68}Ga$

$^{62}Zn/{}^{62}Cu$

- Y – Sr ${}^{87}_{39}Y^{*}_{48} \rightarrow {}^{87m}_{38}Sr^{*}_{49} + \beta^+ + \nu + E$ (80,3 h)
  $$\searrow {}^{87}_{38}Sr^{*}_{49} + \gamma \quad (388\,keV;\ 2{,}81\,h)$$