GHENT UNIVERSITY

European Commission

juas
Joint Universities Accelerator School

LOW-ENERGY ELECTRON ACCELERATORS

Applications in medicine and industry PART 2

Wim Mondelaers

Ghent University
and
Joint Research Centre
the European Commission's
in-house science service

Joint Research Centre

1

Low-energy electron machines

1. Basic principles of X-ray production
   → *bremsstrahlung*
   → *synchrotron radiation*

2. Physical, chemical and biological aspects of the application of electrons and bremsstrahlung photons

3. Electron accelerators in medicine **Gy - range** ←

4. Electron accelerators in industry **kGy - range**

5. Electron storage rings for medicine and industry

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Radiation field requirements

BEAM

- well defined
- variable in size
- moveable in three dimensions
- variable energy
- variable intensity
- X-ray ⇔ electron mode
- pure and well-confined

TREATMENT UNIT

- reliable and reproducible
- easy maneuvrable
- simple and fail-safe
- very compact

DOSE RATE

- high
- irradiation time ~ 1/2 minute
- accurately monitored
- fail-safe feedback to accelerator

DOSE DISTRIBUTION

- uniform or
- non-uniform in predefined way
- controllable
- reproducible
- stable

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Machine requirements

• energy range	4 - 25 MeV
• intensity range	0.5 - 50 μA
• dose rates	1 - 4 Gy / min
• number of electron energies	5
• number of X-ray energies	2
• homogeneity of X-ray fields	5 % over 40 x 40 cm^2
• homogeneity of electron fields	5 % over 25 x 25 cm^2
• leakage doses	below 10^{-3} at 1 m
• gantry rotation	360°
• isocentre definition	1 mm
• degrees of freedom	15 (rotation and translation)
• good defintion at target	energy, position, direction
• volume	5 x 3 x 3 m^3

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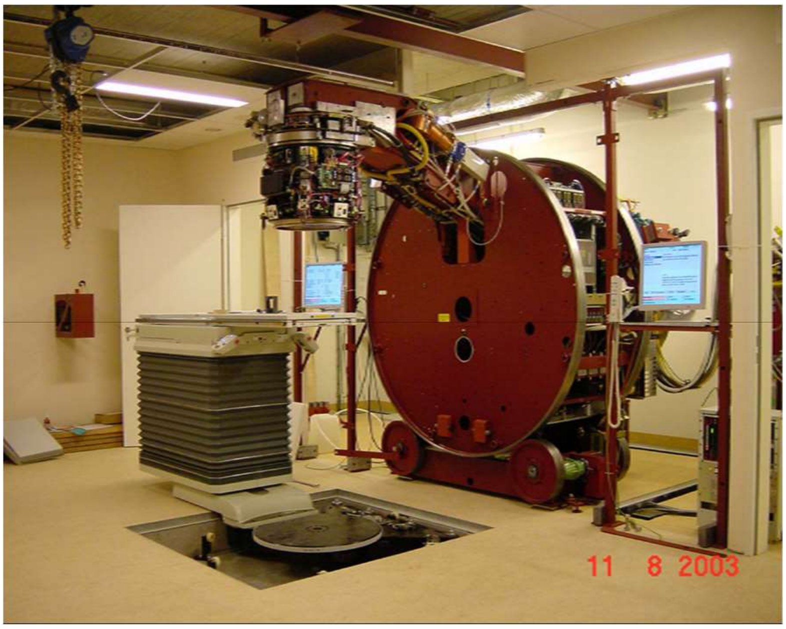
5



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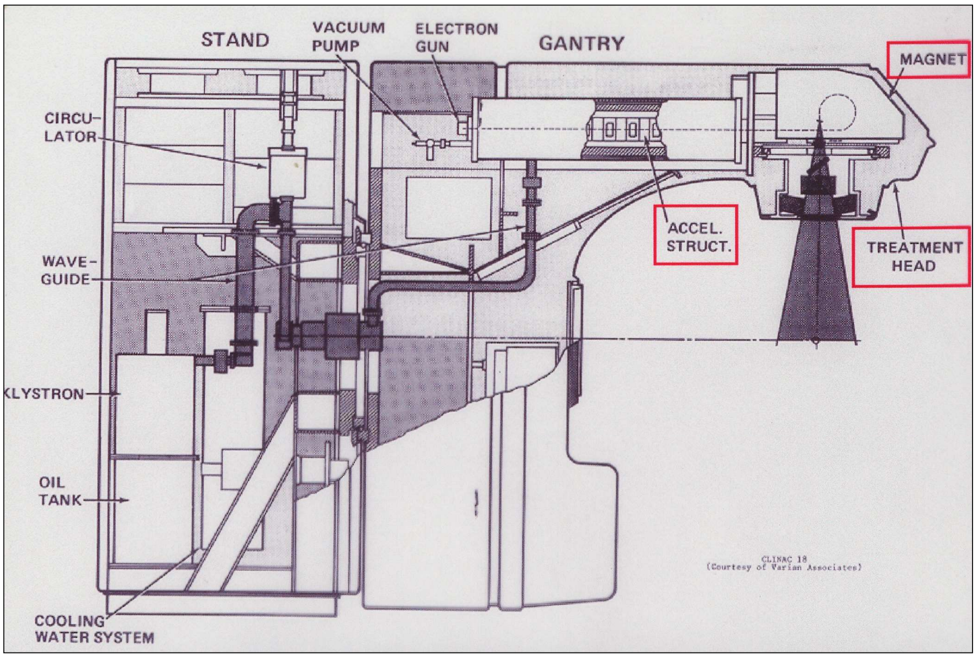
6



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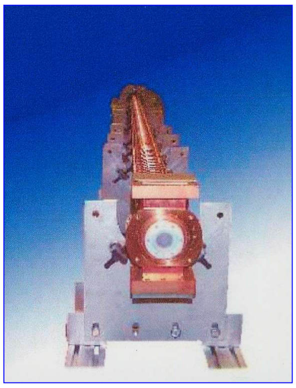
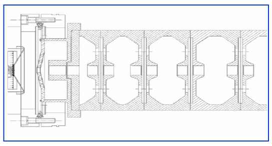
Accelerating structures





Energy:	4 - 25 MeV	
Length:	~ 1 m	
HF power:	2 - 5 MW_p	magnetron
	5 - 20 MW_p	klystron

Disc-loaded waveguides

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Energy of the electron accelerator

$$V = \sqrt{(1-e^{-2\tau})P_0R_0L} - \frac{R_0LI}{2}\left[1-2\tau\frac{e^{-2\tau}}{1-e^{-2\tau}}\right]$$

V = energy of accelerator section in MeV
L = length accelerator structure in meters
P_0 = high-frequency peak power in MW
R_0 = shunt impedance in MΩ/m
τ = attenuation constant
I = accelerated peak current in Amperes

Shunt impedance ↑↑

$$R_0 = -\frac{E_0^2}{\frac{dP}{dz}}$$

- travelling wave structure
- standing wave structure ⟶
  - biperiodic structure
  - side-coupled structure

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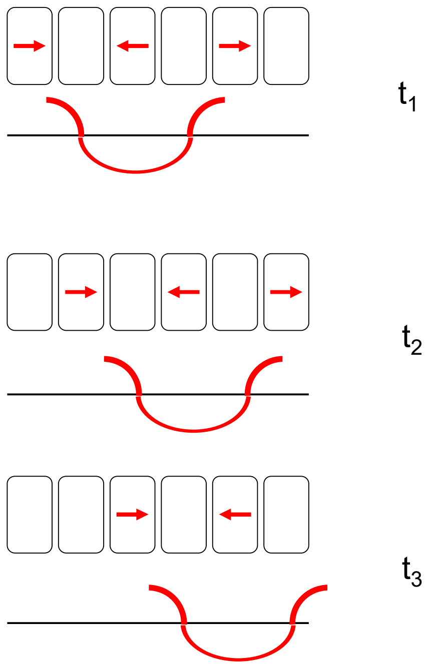
9

Travelling wave



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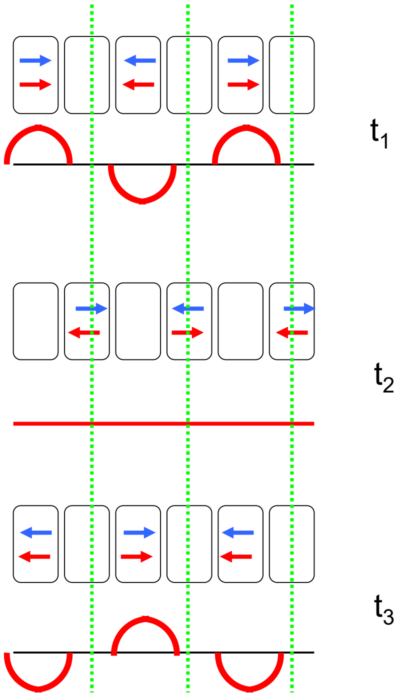
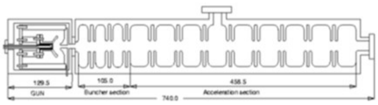
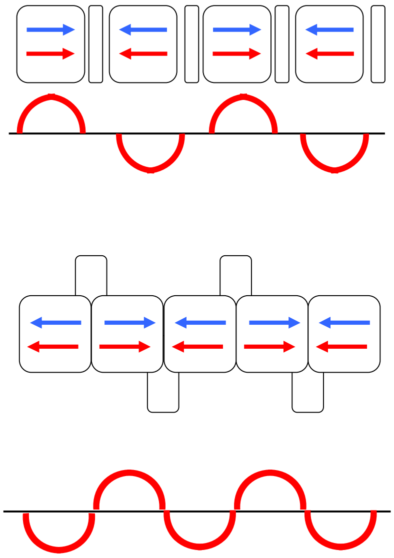
10

Standing wave

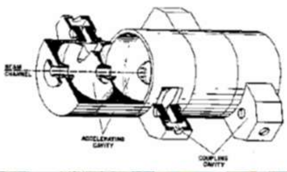


Bi-periodic structure





Side-coupled structure

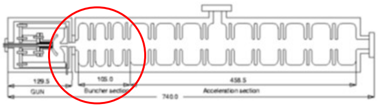


Energy variation

1. Variation of input power P_0 or accelerated current I

$$V = \sqrt{(1-e^{-2\tau})P_0 R_0 L} - \frac{R_0 L I}{2}\left[1 - 2\tau\frac{e^{-2\tau}}{1-e^{-2\tau}}\right]$$

BEAM LOADING



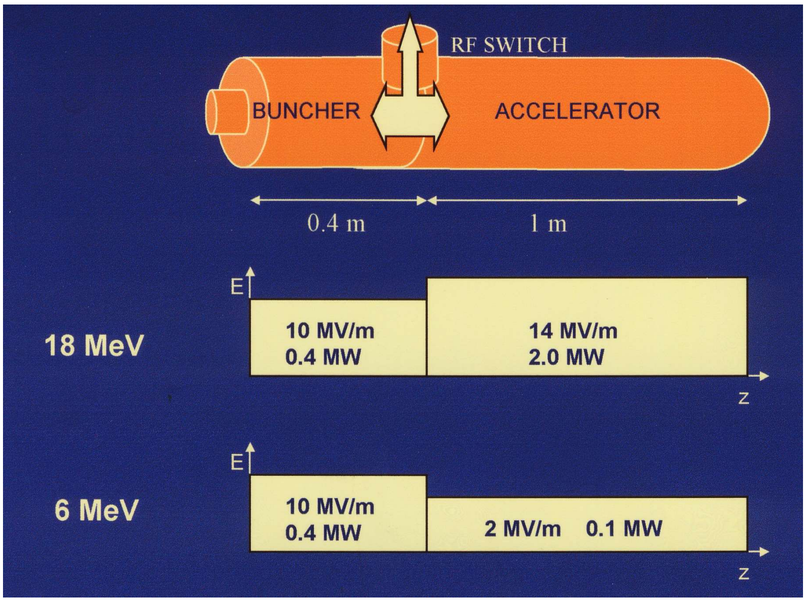
2. Variation of RF frequency

Variation of phase velocity fixed by design

Variation of e^- velocity
~ accelerating gradient
~ power P_0

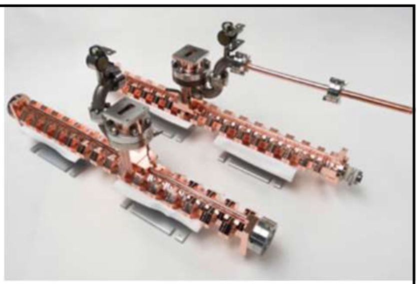
Energy variation

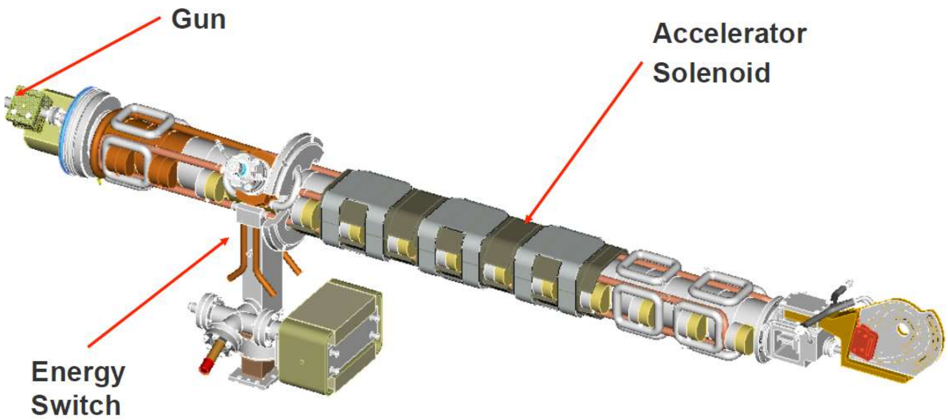
3. Buncher + accelerator section



Energy variation

3. Buncher + accelerator section





15

Electrons in bending magnet systems

Magnetic rigidity $$\chi_b = B\rho = \frac{1}{299.79}\sqrt{V(V+1.022)}$$

V = energy of electrons in MeV
B = magnetic field induction in Tesla
ρ = bending radius in meters

Excitation of room-temperature magnet $$NI \approx \frac{B}{\mu_0} g$$

NI = number of Ampere-turns
B = magnetic field induction in Tesla
g = gap between magnet poles in meters
μ_0 = $4\pi.10^{-7}$ Tm/A

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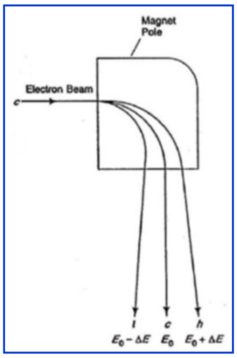
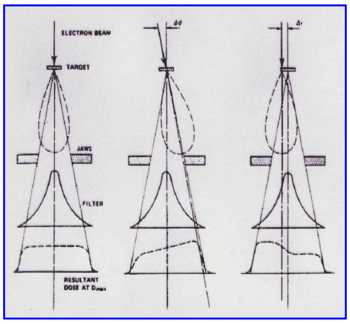
16

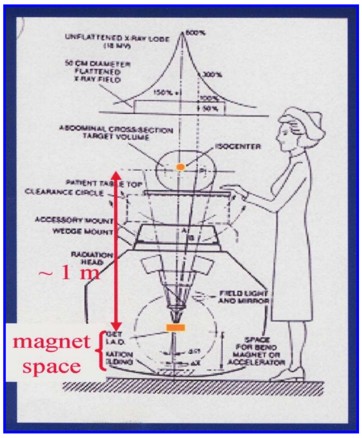
Bending magnet systems

$$x_1 = m_{11}x_0 + m_{12}x'_0 + m_{13}\frac{\Delta p}{p}$$
$$x'_1 = m_{21}x_0 + m_{22}x'_0 + m_{23}\frac{\Delta p}{p}$$



Energy spread
medical ~ 10 %
research < 1 %





Bending magnet systems

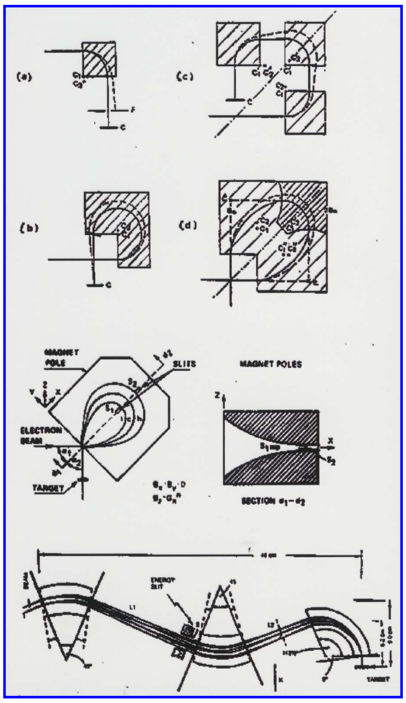
TRANSPORT calculations

Drift pieces

Homogeneous bending magnets

Weak focusing bending magnets

Homogeneous bending magnets
with rotated pole shoe edges



Bending magnet systems — TRANSPORT calculations

DRIFT PIECE Length L

$$M_H = \begin{pmatrix} 1 & L & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad M_V = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$

HOMOGENEOUS BENDING MAGNET

Length L — Bending angle α — Bending radius ρ

$$M_H = \begin{pmatrix} \cos\alpha & \rho\sin\alpha & \rho(1-\cos\alpha) \\ -\dfrac{\sin\alpha}{\rho} & \cos\alpha & \sin\alpha \\ 0 & 0 & 1 \end{pmatrix} \qquad M_V = \begin{pmatrix} 1 & \rho\alpha \\ 0 & 1 \end{pmatrix}$$

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19

Bending magnet systems — TRANSPORT calculations

WEAK FOCUSSING BENDING MAGNET Field index 0 < n < 1

Length L — Bending angle α — Bending radius ρ

$$M_H = \begin{pmatrix} \cos\sqrt{1-n}\alpha & \dfrac{\rho\sin\sqrt{1-n}\alpha}{\sqrt{1-n}} & \dfrac{\rho(1-\cos\sqrt{1-n}\alpha)}{1-n} \\ -\dfrac{\sqrt{1-n}\sin\sqrt{1-n}\alpha}{\rho} & \cos\sqrt{1-n}\alpha & \dfrac{\sin\sqrt{1-n}\alpha}{\sqrt{1-n}} \\ 0 & 0 & 1 \end{pmatrix}$$

$$M_V = \begin{pmatrix} \cos\sqrt{n}\alpha & \dfrac{\rho\sin\sqrt{n}\alpha}{\sqrt{n}} \\ -\dfrac{\sqrt{n}\sin\sqrt{n}\alpha}{\rho} & \cos\sqrt{n}\alpha \end{pmatrix}$$

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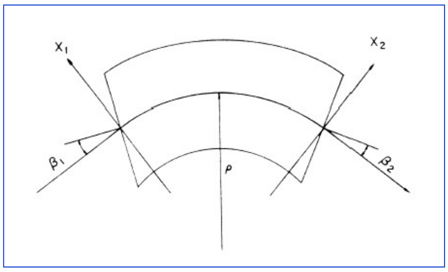
20

HOMOGENEOUS BENDING MAGNET with ROTATED POLE SHOE EDGES

Length L Bending angle α Bending radius ρ

β_1 angle of pole edge rotation at entrance

β_2 angle of pole edge rotation at exit



$$M_H = \begin{pmatrix} 1 & 0 & 0 \\ \frac{\tan\beta_2}{\rho} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\alpha & \rho\sin\alpha & \rho(1-\cos\alpha) \\ -\frac{\sin\alpha}{\rho} & \cos\alpha & \sin\alpha \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ \frac{\tan\beta_1}{\rho} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$M_V = \begin{pmatrix} 1 & 0 \\ -\frac{\tan\beta_2}{\rho} & 1 \end{pmatrix} \begin{pmatrix} 1 & \rho\alpha \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{\tan\beta_1}{\rho} & 1 \end{pmatrix}$$

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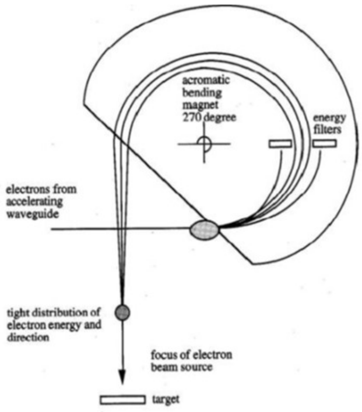
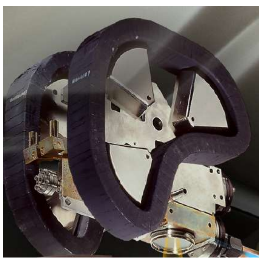
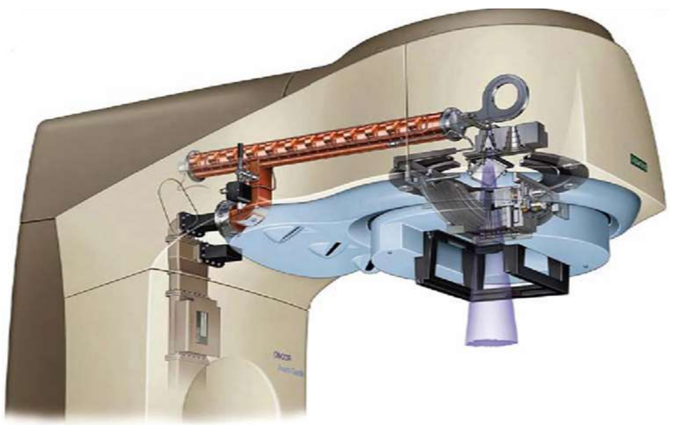
21

Bending magnet systems







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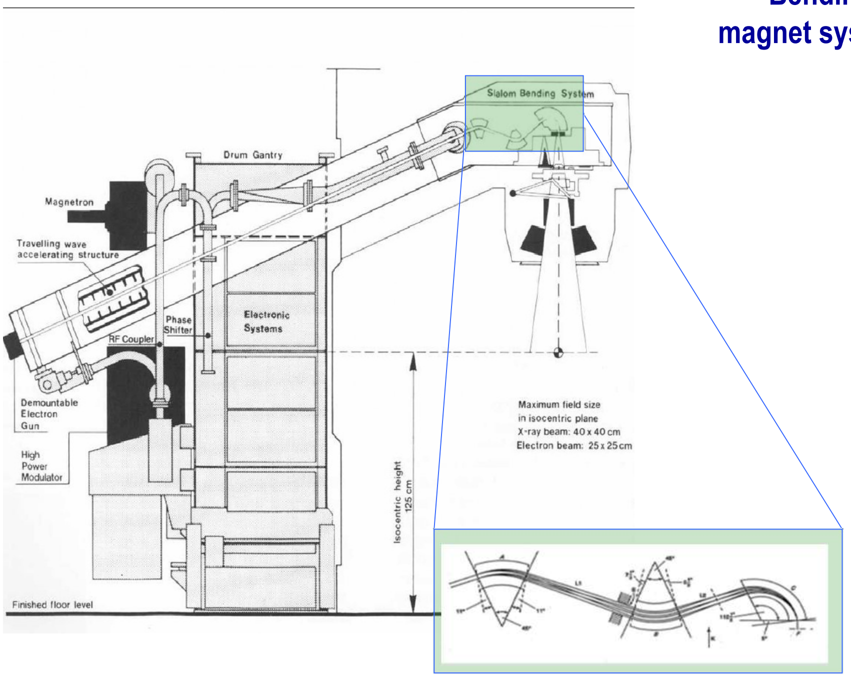
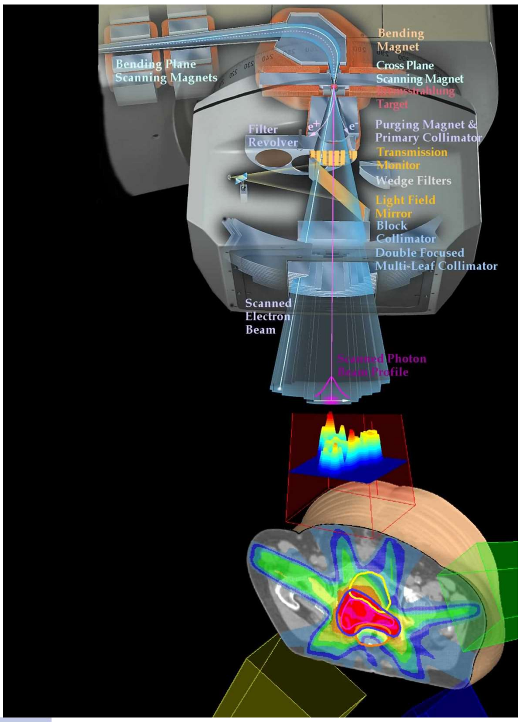
22

Bending magnet systems

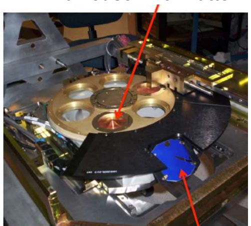




Treatment head

Multileaf collimator

Carrousel with flattening filter



Optical mirror

Modern trends

- intensity-modulated arc radiotherapy
- thomotherapy
- image-guided radiotherapy
- stereotactic radiosurgery
- intra-operative radiotherapy

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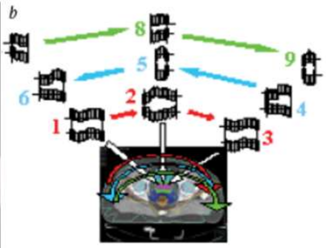
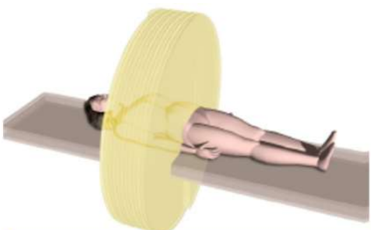
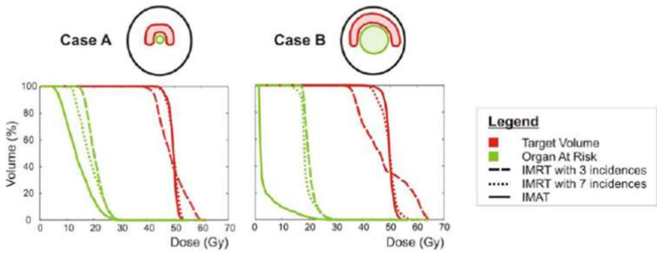
25

IMAT

Thomotherapy







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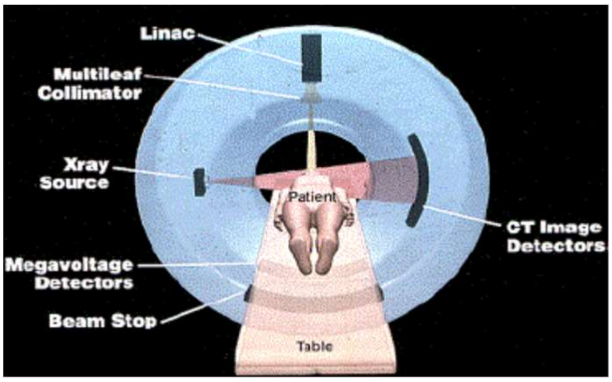
26

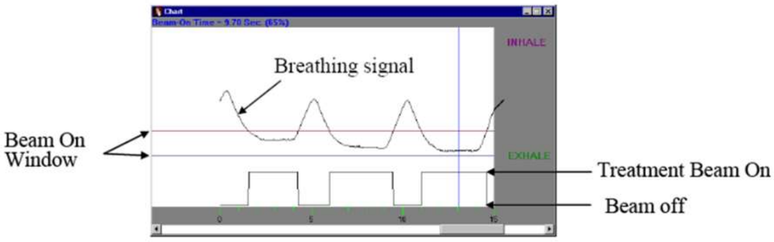
Image-guided radiotherapy

CT scan and linac in one



Positional changes:

- during irradiation
- between fractions
- shrinkage of tumour



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27

Stereotactic radiosurgery

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Linac on a robotic arm

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28

Intra-operative radiotherapy

intracorporal

extracorporal

Extracorporal bone tumours therapy

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29

Intraoperative extracorporal irradiation in primary bone tumours therapy

One operative session:

- excission of bone
- extracorporal irradiation 300 Gy
- reimplantation

Homogeneous photon irradiation field

- homogeneity ± 2 %
- diameter 20 cm
- dose rate 3 Gy / s

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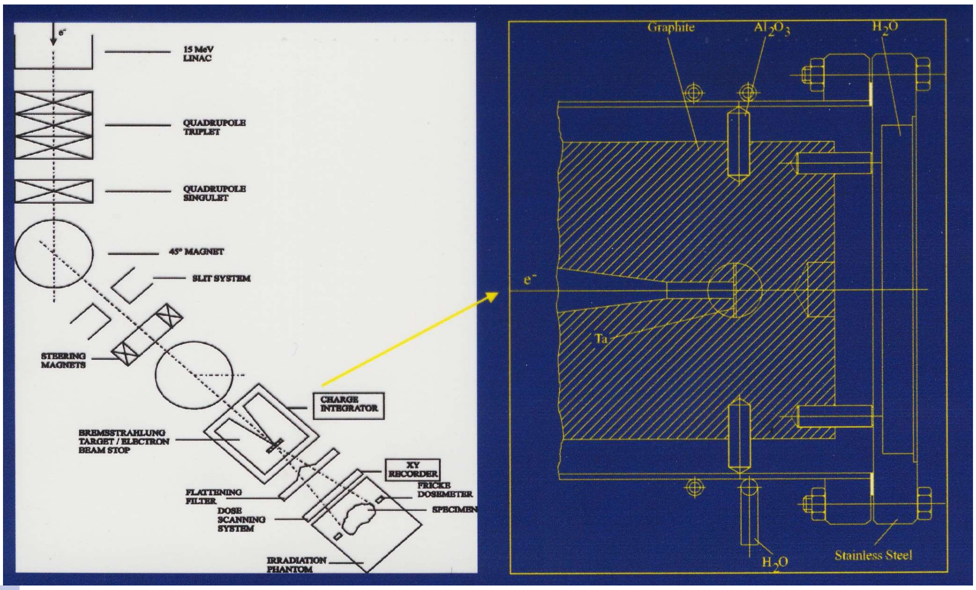
Extracorporeal bone tumours irradiation

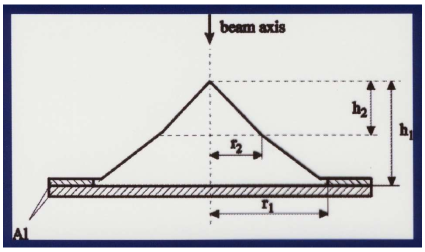
Dose rate: 3 Gy / s

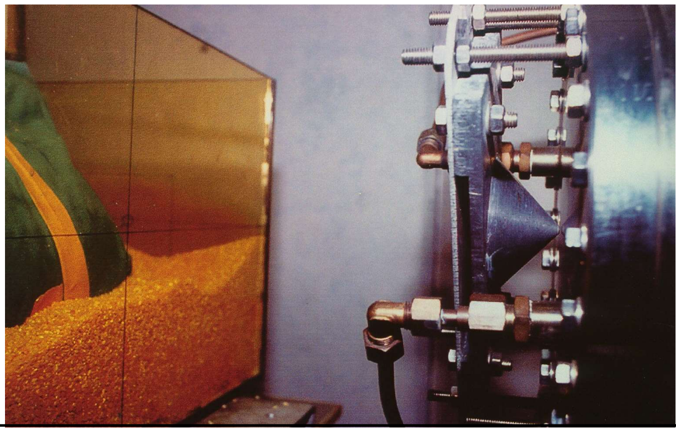


31

Extracorporeal bone tumours irradiation

Homogeneity
< 2 %





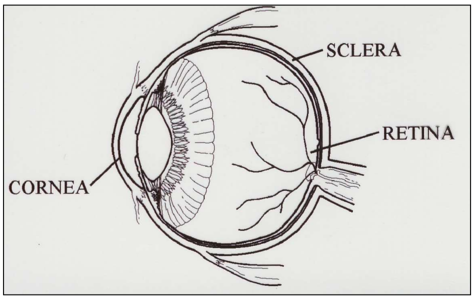
32

Radiation treatment of human grafts and artificial implants

- **sclerae of the human eye**

prosthesis → imflammation
rejection

⇒ 'packed' in human sclerae
- less reactions
- synchronous movement



lyophylisation → sterilisation 25 kGy → tissue bank

- **bone fragments:** maxillo-facial reconstruction
- **human implants:** cardiological stents, polymeric implants, hydrogels
- **blood products:** lymphocytes 40 Gy (graft-versus-host disease)

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33

Electron accelerators in medicine

- Radiotherapy

- Radioisotope production

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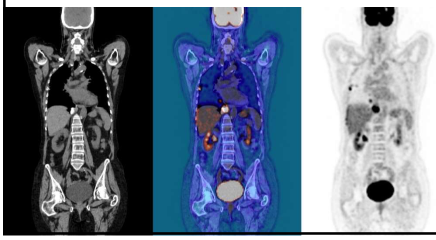
34

Medical radioisotope production

Diagnostic imaging
- SPECT
- PET

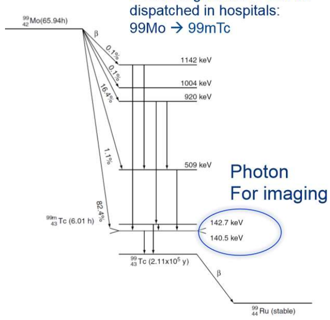
Radiotherapy
- β^- emitters
- α emitters

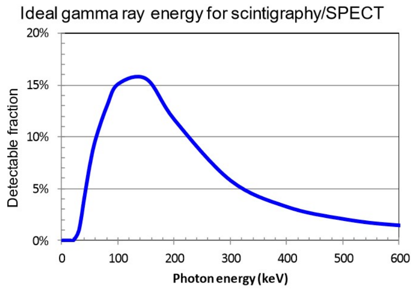
Medical Isotope	Life-time $T_{1/2}$	Use	Nuclear Reaction	Target Abun-dance (%)	Energy Range (MeV)	Production Yield (mCi @ sat)	Typical Dose (mCi)
^{11}C	20.4m	PET	$^{11}B(p,n)$	80.3	8 - 20	40/µA	
^{11}C	20.4m	PET	$^{14}N(p,\alpha)$	99.6	12	100/µA	
^{11}C	20.4m	PET	$^{10}B(d,n)$	19.7	7	10/µA	
^{13}N	9.96m	PET	$^{13}C(p,n)$	1.1	5 - 10	115/µA	
^{13}N	9.96m	PET	$^{12}C(d,n)$	98.9	2 - 6	50/µA	
^{13}N	9.96m	PET	$^{16}O(p,\alpha)$	99.8	8 - 18	65/µA	
^{15}O	2m	PET	$^{15}N(p,n)$	0.36	10 - 15	47/µA	
^{15}O	2m	PET	$^{16}O(p,pn)$	99.8	>26	25/µA	
^{15}O	2m	PET	$^{14}N(d,n)$	99.6	8 - 6	27/µA	
^{18}F	109.8m	PET	$^{18}O(p,n)$	0.20	8 - 17	180/µA	5 - 20
^{18}F	109.8m	PET	$^{20}Ne(d,\alpha)$	90.5		82/µA	
^{64}Cu	12.7h	SPECT	$^{64}Ni(p,n)$	0.93	5 - 20	5/µA	
^{67}Cu	61.9h	SPECT	$^{68}Zn(p,2p)$	19.0	>40	0.02/µA	
^{67}Ga	78.3h	SPECT	$^{68}Zn(p,2n)$	19.0	20 – 40	4.5/µA	10
$^{82}Sr/^{82m}Rb$	25d/5m	PET	$^{85}Rb(p,4n)^{82}Sr$ Produces Rb	72.2	50 -70	0.18 /µAh	
^{99m}Tc	6h	SPECT	$^{100}Mo(p,2n)$	9.7	19	14/µAh	20
^{103}Pd	17.5d	Therapy	$^{103}Rh(p,n)$	100	10 -15	0.32/µAh	
^{111}In	67.2h	SPECT	$^{112}Cd(p,2n)$	24.1	18 - 30	6/µAh	3
^{123}I	13.2h	SPECT	$^{124}Xe(p,2n)^{123}Cs \rightarrow ^{123}Xe \rightarrow ^{123}I$	0.10	25 - 35	27/µAh	
^{123}I	13.2h	SPECT	$^{123}Te(d,2n)\ ^{123}I$	0.89	10 - 15	20/µAh	
^{124}I	4.1d	PET	$^{124}Te(p,n)$	4.7	10 - 18	0.1/µAh	
^{124}I	4.1d	PET	$^{124}Te(d,2n)$	4.7	>20	0.15/µAh	
^{186}Re	90.6h	Therapy /SPECT	$^{186}W(p,n)$	28.4	18		
^{201}Tl	73.5h	SPECT	$^{203}Tl(p,3n)^{201}Pb \rightarrow ^{201}Tl$	29.5	27 - 35	0.7/µAh	4
^{211}At	7.2h	Therapy	$^{209}Bi(\alpha,n)$	100	28	1/µAh	0.05-.01



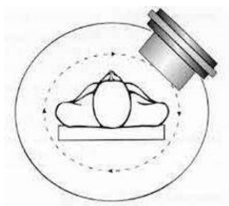
^{99m}Tc is the most widely used isotope in nuclear medicine

So called generators can be dispatched in hospitals:
99Mo → 99mTc

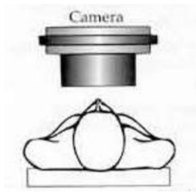




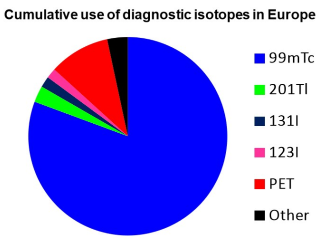
10 cm soft tissue, 0.2 cm aluminium (detector encapsulation), 1 cm NaI



3D: SPECT: Single Photon Emission Computer Tomography



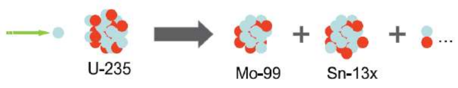
2D: planar scan (Gamma camera)

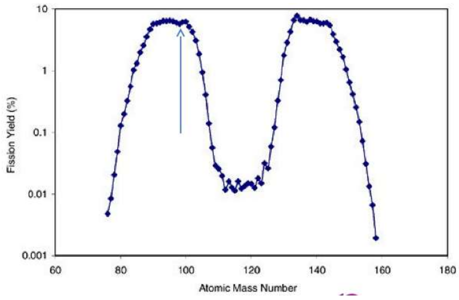


Current ^{99}Mo reactor-based production processes

REACTORS

- Fission of HEU $^{235}U(n,F)^{99}Mo$





- Neutron capture $^{98}Mo(n,\gamma)^{99}Mo$

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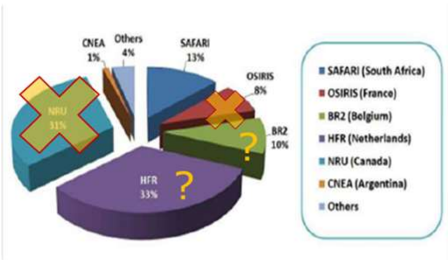
37

EUROPEAN OBSERVATORY on the supply of medical radioisotopes

Press Release

The European Commission and the Nuclear Medicine Industry have jointly created *a European Observatory on the Supply of Medical Radioisotopes.*

' Following the **shortages of medical radioisotopes** across the globe between 2008 and 2010 due to **unplanned reactor shutdowns**, the Council of the EU issued Council Conclusions "Towards the Secure Supply of Radioisotopes for Medical Use in the EU", asking the European Commission to define a European solution for **ensuring** mid and long term **security of supply of radioisotopes within the EU**.'



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Archive > Volume 504 > Issue 7479 > News Feature > Article

NATURE | NEWS FEATURE

Radioisotopes: The medical testing crisis

With a serious shortage of medical isotopes looming, innovative companies are exploring ways to make them without nuclear reactors.

Richard Van Noorden

11 December 2013

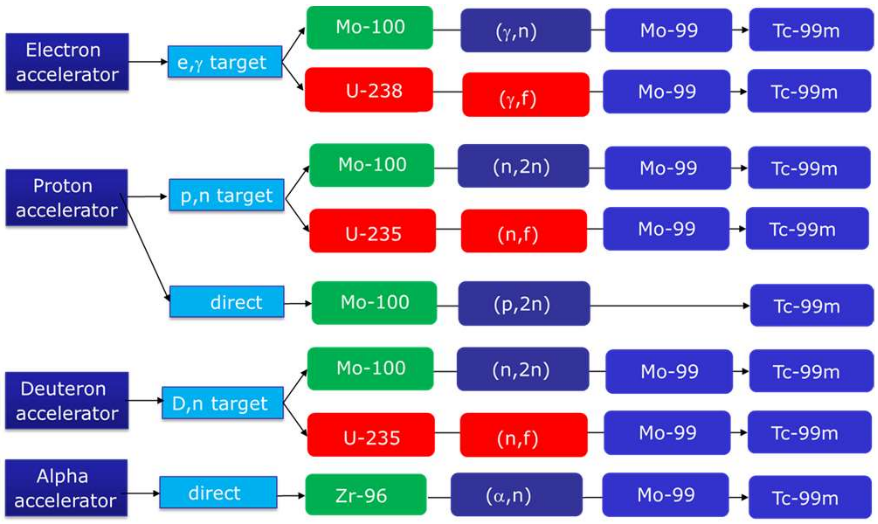
- Major reactors: few and old
  - safety, licensing and decommissioning
- Current production uses highly-enriched ^{235}U
  - nuclear proliferation
  - high-level nuclear waste

ACCELERATORS

WM/ JUAS

38

Accelerator-based alternatives for ^{99}Mo production



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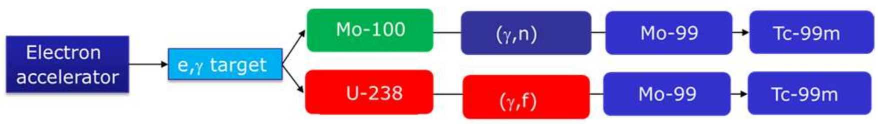
39

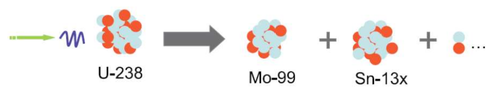
Accelerator-based alternatives for ^{99}Mo production



ELECTRON ACCELERATORS

- Photo-neutron $^{100}Mo(\gamma,n)^{99}Mo$

- Photo-fission $^{238}U(\gamma,F)^{99}Mo$



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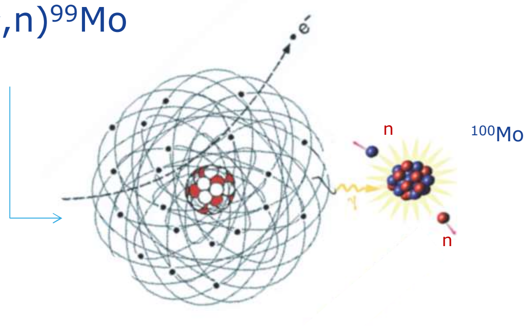
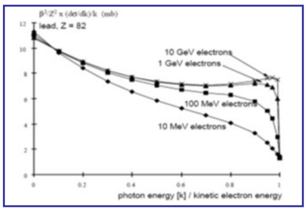
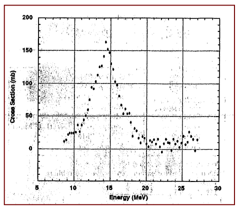
40

Bremsstrahlung target and ^{99}Mo production

$^{100}Mo(\gamma,n)^{99}Mo$







→ Target : disk of high-Z material
high melting point solid e.g. W or U