EUROPEAN COMMISSION
Joint Research Centre

JUAS
Joint Universities Accelerator School

LOW-ENERGY ELECTRON ACCELERATORS
Applications in Medicine and Industry

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Joint Research Centre

irmm

Accelerators in the world

year 2007 *
(approximate numbers)

APPLICATION	
High-energy physics research	120
Synchrotron radiation sources	50
Ion beam analysis	200
Photon or electron therapy	9100
Hadron therapy	30
Radioisotope production	550
Ion implantation	9500
Neutrons for industry or security	1000
Radiation processing	2000
Electron cutting and welding	4500
Non-destructive testing	650
TOTAL	27700

* R. Hamm
at 9th ICFA Seminar
October 30, 2008

~ 60% low-energy electron accelerators

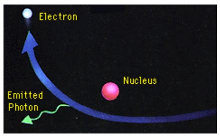
Low-energy electron machines

X-rays — electrons

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
4. Electron accelerators in industry
5. Electron storage rings for medicine and industry

Radiation of electrons in a transverse field

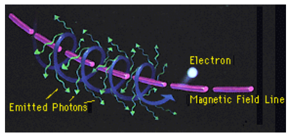
Coulomb field of atomic nuclei



BREMSSTRAHLUNG

braking radiation

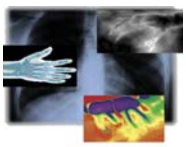
Magnetic field



SYNCHROTRON RADIATION

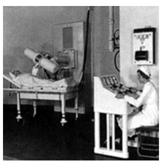
$$P = \frac{q^2\gamma^2}{6\pi\varepsilon_0 m_o^2 c^3}\left(\frac{d\vec{p}}{dt}\right)^2$$

Low-energy electron accelerators in medicine



1895 Röntgen
discovery of X-rays

1896 Becquerel
discovery of radioactivity



diagnosis → X-ray radiography

treatment → X-ray radiotherapy → Radioactive sources

skin-sparing ↑
side scatter ↓
depth-dose ↑

← Accelerator-based radiotherapy

Accelerator-based radiotherapy

1937 first hospital-based VAN DE GRAAFF

1946 first hospital-based BETATRON + WILSON: use of protons and ions

1952 first hospital-based RF LINAC

1990 first hospital-based PROTON SYNCHROTRON

<u>Now</u> electrons and photons: routine therapy ⇓ conformal therapy

protons and ions: unconventional

Low-energy electron accelerators in industry

1905 APPLEBY and MILLER, patent:
'use of X-rays to bring about an improvement in the conditions of foodstuffs'

1956 JOHNSON and JOHNSON
sterilisation of medical devices

INDUSTRY	radiation processing
in a car:	dashboard, tyres, cables, painting ...
in an airplane:	constructional components ...
at the doctor:	syringes, pharmaceuticals, sterile dressings ....
in the supermarket:	strawberries, red meat, shrink packaging materials ...
in the clothing shop:	permanently-creased trousers or T-shirts, raincoats ...
at home:	electrical cables, parquet ....
in the human body:	prostheses, catheters, advanced drug-delivery systems ...

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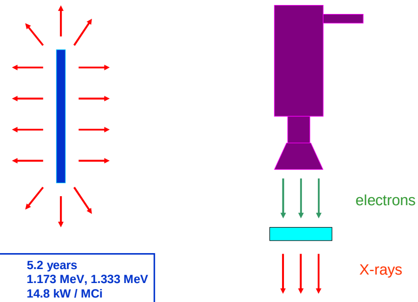
γ - rays | electrons | X - rays



^{60}Co	5.2 years 1.173 MeV, 1.333 MeV 14.8 kW / MCi
^{137}Cs	30.2 years 0.622 MeV 3.3 kW / MCi

5 MeV photons
10 MeV electrons

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Bremsstrahlung production

COLLISION STOPPING POWER → HEAT !!!

$$-\left(\frac{dT}{dx}\right)_c = 2\pi\frac{e^4NZ}{m_e\beta^2c^2}\left[\ln\frac{m_e\beta^2c^2T}{2I^2(1-\beta^2)}+(1-\beta^2)-\ln2\left(2\sqrt{1-\beta^2}-1+\beta^2\right)+\frac{\left[1-\sqrt{1-\beta^2}\right]^2}{8}\right]$$

BREMSSTRAHLUNG STOPPING POWER

$$-\left(\frac{dT}{dx}\right)_r = \frac{NTZ(Z+1)e^4}{137m_e^2c^4}\left[4\ln\left(\frac{2T}{m_ec^2}\right)-\frac{4}{3}\right]$$

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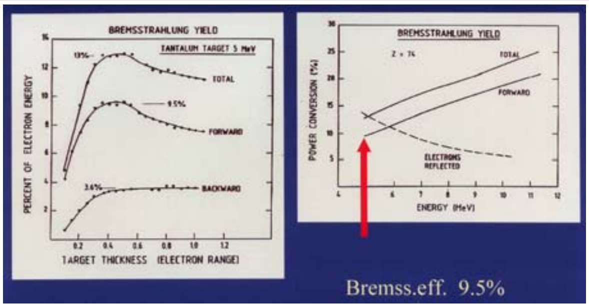

1 MCi of ^{60}Co ↔ 5 MeV / 155 kW

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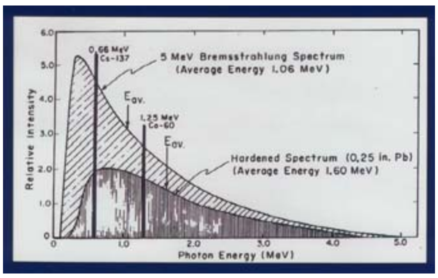

BREMSSTRAHLUNG SOURCE:
- forward-peaked
- on / off
- Cobalt 12.4% / year ↓
- no nuclear waste
- X-ray and electron mode

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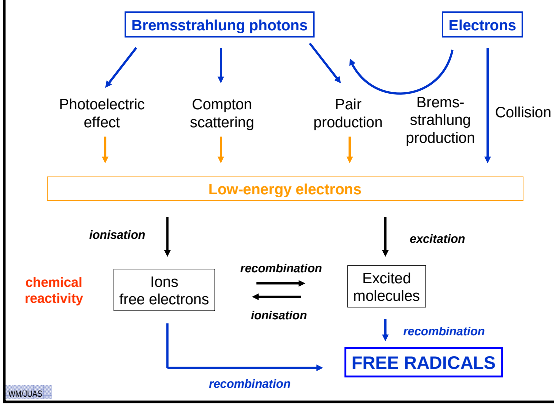

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FREE RADICALS

↓

- damage DNA — *radiotherapy*, *food irradiation*, *sterilisation*
- chain reaction — R° + AB → R- AB°; R- AB° + AB → R- AB-AB° — *polymer chemistry*
- special chemical reactions — *radiation synthesis*
- graft a second polymer — *curing*, *biomaterials*

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Physical, chemical and biological effects
~ deposited energy

↓

DOSE = deposited energy per unit mass

1 Gray = 1 J / kg

1 Gy = 100 rad

4.2 kGy in water → 1° C

⇒ high yields of reactive species at low temperatures

ELECTRONS or PHOTONS
similar end products
different spatial distributions

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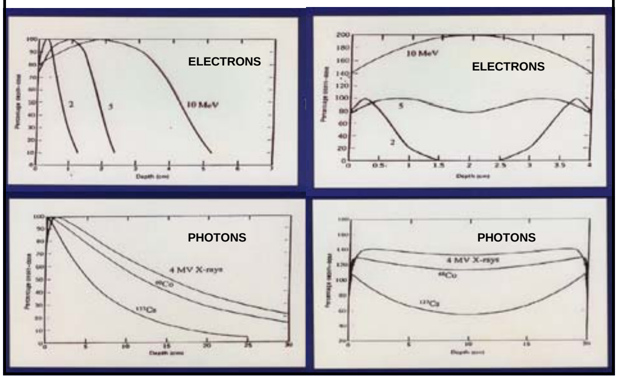
Single-sided irradiation — Double-sided irradiation



PATIENT — Initial physical, chemical and biological properties — **MATERIAL**

⇩ **RADIATION**

TREATED PATIENT — Altered physical, chemical and biological properties — **PROCESSED MATERIAL**

⇩ Quality of life ↑, % survival ↑ — ⇩ Quality ↑, new features

!!! Minimum of side effects !!!

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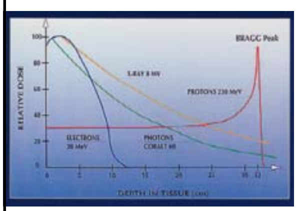
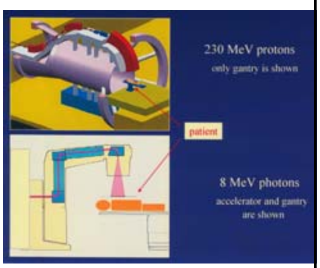
Low-energy electron accelerators in medicine

Why X-rays or electrons ?





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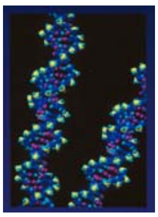
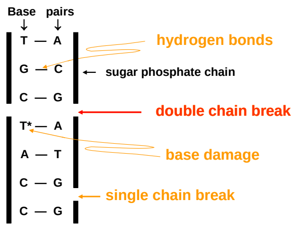
Photons and electrons in radiotherapy



Radiation damage to DNA:
- direct
- indirect by free radicals and reactive species



Repair mechanisms

60 Gy survival probability 10^{-9}

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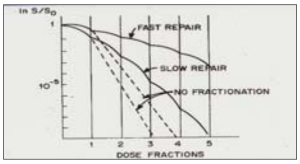
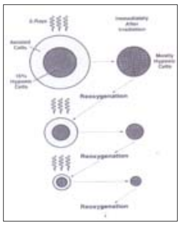
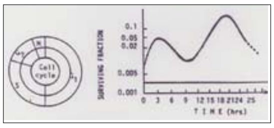
Dose fractionation

- dose-dependent survival fraction
- oxygenation
- radiosensitivity during cell cycle







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Radiotherapy

30 fractions of 2 Gy

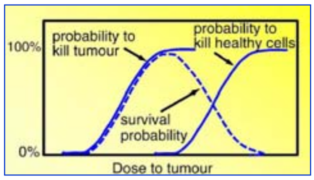
4 Gy / min

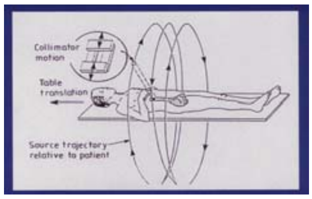
40 x 40 cm^2

⇩

Accuracy of dose delivery
± 3.5 %

Treatment dose
PLANNING
DELIVERY





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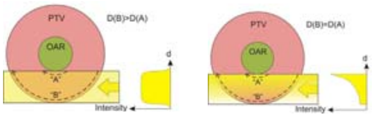
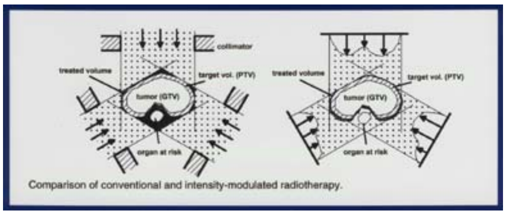
Conformal therapy : IMRT





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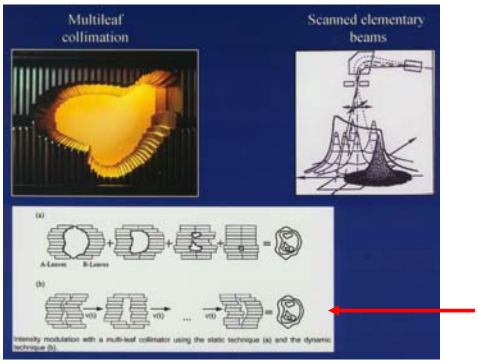
IMRT



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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
- 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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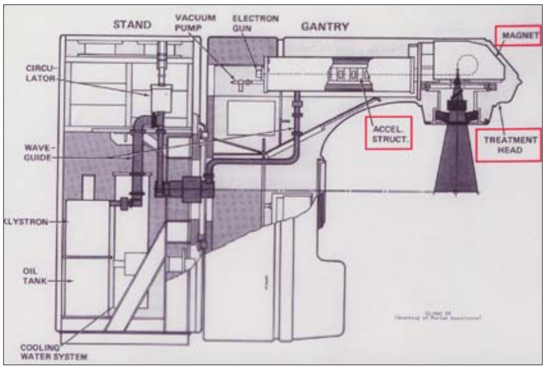

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Accelerating structures

Energy: 4 - 25 MeV

Length: ~ 1 m

HF power: 2 - 5 MW_p magnetron; 5 - 10 MW_p klystron

Disc-loaded waveguides

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

- travelling wave structure → • biperiodic structure
- standing wave structure • side-coupled structure

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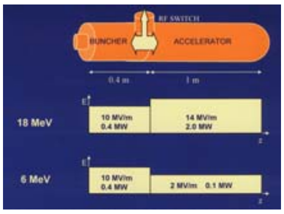
Energy variation

1. Variation of input power P_0 or accelerated current I

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

2. Variation of RF frequency

3. Buncher + accelerator section



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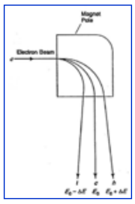
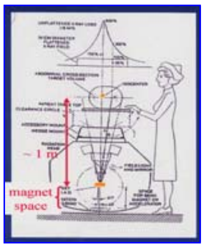
Bending magnet systems

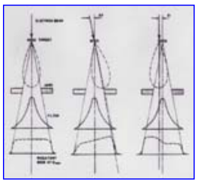
$$x_1 = m_{11}x_0 + m_{12}x_0' + m_{13}\frac{\Delta p}{p}$$

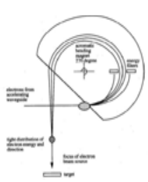
$$x_1' = m_{21}x_0 + m_{22}x_0' + m_{23}\frac{\Delta p}{p}$$



Energy spread
medical ~ 10 %
research < 1 %







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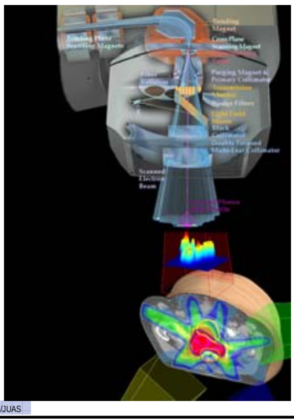
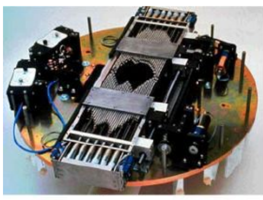
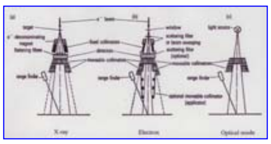


Treatment head



Multileaf collimator



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New trends

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

Extracorporal bone tumours therapy

GHENT UNIVERSITY

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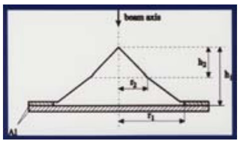
Extracorporeal bone tumours irradiation

Homogeneity
< 2 %



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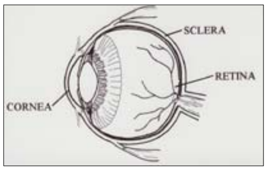
Radiation treatment of human grafts and artificial implants

• **sclerae of the human eye**

prosthesis → inflammation
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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Low-energy electron accelerators in medicine

BEAM POWER =
ENERGY x INTENSITY

Energy
< 10 MeV electrons
< 5 MeV photons

~ penetration depth

DOSE RATE
⇓
INTENSITY

150 KW

5 MeV / 30 mA
0.5 MeV / 300 mA

ACCELERATORS
3 energy ranges

0.1 – 0.5 MeV
0.5 – 5 MeV
5 – 10 MeV

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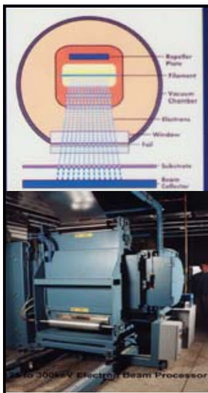
Energy range 0.1 - 0.5 MeV



BROAD BEAM

Single-stage machines

• self-shielding
• low penetration capability
• integrated in production line
• beam widths ~ 2.5 m

SCANNING TYPE

APPLICATIONS:
surface treatment
irradiation of coatings, adhesives, inks
e.g. thin film packaging
printing industry

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Energy range 0.5 - 5 MeV

Multi-stage machines

• high penetration capability
• up to 300 kW
• beam widths ~ 2 m

COCKROFT-WALTON

INSULATED-CORE TRANSFORMER

DYNAMITRON

APPLICATIONS: processing of thick sheets
wires and cables
tubes and pipes
fiber composites
tire components
heat-shrinkable products
foamed polyethylene

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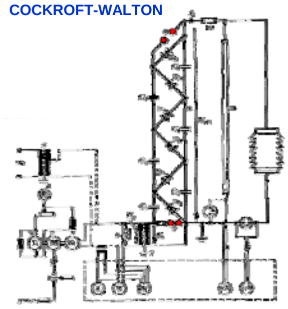
Energy range 0.5 - 5 MeV

COCKROFT-WALTON



Greinacher cascade generator

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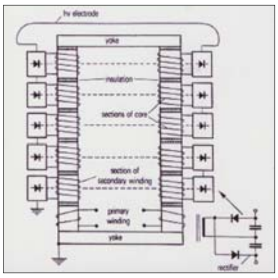
Energy range 0.5 - 5 MeV

INSULATED-CORE TRANSFORMER



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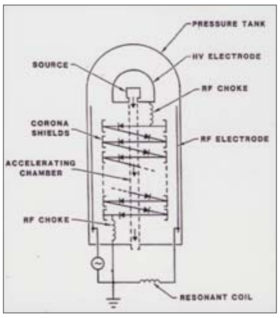
Energy range 0.5 - 5 MeV

DYNAMITRON



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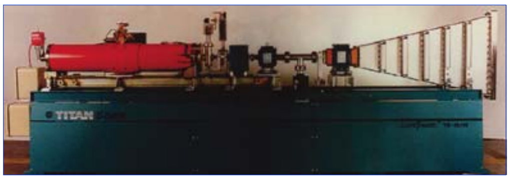
Energy range 5 - 10 MeV

RF linear accelerator	→	**50 kW**
RHODOTRON	→	**200 kW up to 1 MW**

APPLICATIONS:
< 5 MeV applications
medical sterilisation
food processing
polymer crosslinking, grafting, degradation

LINAC



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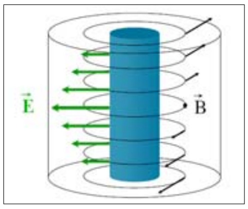
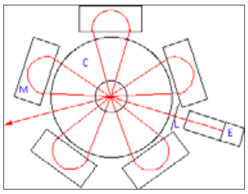
Energy range 5 - 10 MeV

RHODOTRON

$$E = \frac{E_0}{r}\cos 2\pi\frac{z}{\lambda}\sin(\omega t + \varphi)$$

$$B = \frac{B_0}{r}\sin 2\pi\frac{z}{\lambda}\cos(\omega t + \varphi)$$





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INDUSTRIAL APPLICATIONS of ELECTRONS and BREMSSTRAHLUNG

1. POLYMER CHEMISTRY
   - → *crosslinking*
   - → *grafting*
   - → *curing*
   - → *degradation*
2. STERILISATION
3. FOOD TREATMENT
4. RADIOGRAPHY
5. WELDING AND CUTTING

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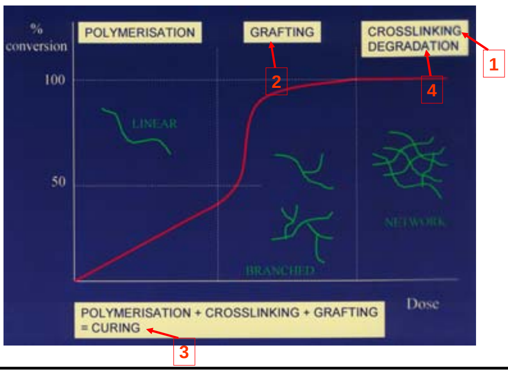
POLYMER CHEMISTRY : irradiation of monomers



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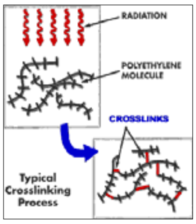
CROSSLINKING



Linear molecule → 3D structure
e.g. polyethylene

⇩

≠ physical properties

- heat resistance ↑↑
- insulation properties ↑
- mechanical strength ↑
- breakdown voltage ↑
- chemical resistance ↑
- creep ↑
- 'memory effect'

- cable insulation
- tubes, pipes and mouldings
- heat-shrinkable films
- vulcanisation of rubber and tires
- synthesis of biomaterials

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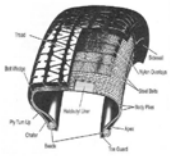
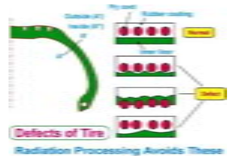
EXAMPLE : **Pre-vulcanisation of tires**



partial crosslinking before the tire is assembled:

- stabilizes thickness of sections during final thermal curing process
- prevents steel belt from migrating through its supporting rubber layer

- improves manufacturability
- better dimensional stability
- higher quality tire
- more uniform thickness
- better balance
- thinner thus generating less frictional



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EXAMPLE : Synthesis of biomaterials

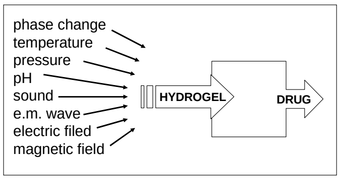
HYDROGELS = crosslinked macromolecular networks swollen in water

- rubbery structure
- substantial water content
- ~ soft living tissue → BIOCOMPATIBLE
- porous network → BIOFUNCTIONAL

- biodegradable polymers
- hydrogels for burn wounds
- porous polymeric hydrogels for advanced drug delivery systems

↓

constant release
signal responsive



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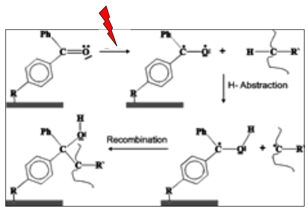
GRAFTING



Polymer backbone + monomer

⇩

≠ surface properties

- biocompatibility
- adhesion
- permeability
- wettability
- chemical resistance
- chemical compatibility
- printability
- hydrophilic / phobic quantities
- functionalisation
- mechanical properties

- finishing of textiles
- adhesion of polyethylene on aluminium
- weak hydrogels on polymeric support
- biofunctional groups on inactive supports

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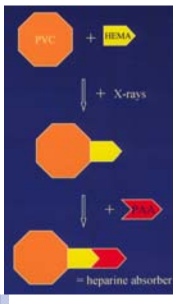
EXAMPLE : Immobilisation of bioactive agents

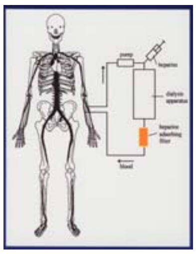
Grafting of biofunctional groups on polymer supports

- HEPARINE FILTER



Hemodyalysis of uremic patients
blood + artificial surfaces → coagulation

heparine adsorbing filters



- FIXATION of HD CELL CULTURES
  → natural skin
  → pancreas cells

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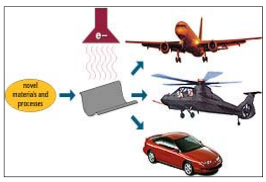
CURING



Polymerisation + crosslinking + grafting

on SURFACES (mainly with electrons)
- antistatic films
- laminates (credits cards, telephone cards)
- offset printing
- door finishing
- parquet coating
- protective films….

in BULK MATERIAL (mainly bremsstrahlung)
- wood-polymer composites
- concrete-polymer composites
- advanced composites

e.g. carbon fiber reinforced epoxies
- automobiles
- aircraft
- ships
- space vehicles
- building materials
- sporting goods
- printed circuit boards

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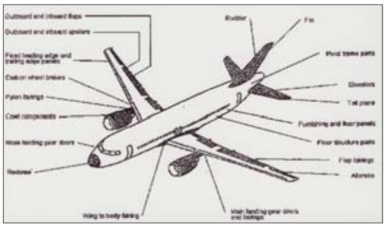
EXAMPLE : On-aircraft repair

Composite materials (carbon-reinforced epoxies):



strength-to-weight ratio ↑
stiffness-to-weight ratio ↑
corrosion resistance
impact damage tolerance
wear properties

⇓

20 - 25 % of aircraft structural weight

AIR CANADA Airbus A320
on aircraft repair with mobile accelerator

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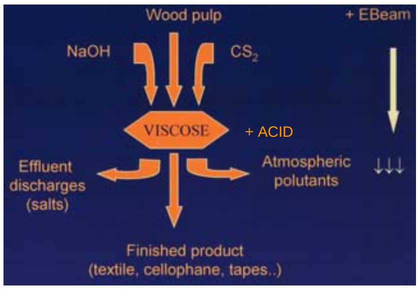
DEGRADATION

• cellulose in viscose industry



• powdered Teflon molecular weight ↓
lubricants, high quality inks

• degradation of pollutants
water, industrial or hospital waste
sewage sludge, flue gases

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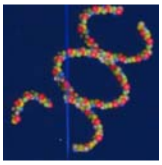

STERILISATION

Radiation killing of pathogenic microorganisms

- energy-efficient (↔ heat)
- low temperature (↔ heat)
- no toxic residues (↔ EtO)
- total sterilisation (↔ EtO)
- no ozon depletion (↔ Met.B.)

- medical disposables

syringes, needles, surgical sutures
wound and burn dressings
gloves, masks, gowns
Petri dishes and pipettes

- medical implants

artificial organs
bone grafts
human eyeballs

- pharmaceuticals
- cosmetics

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FOOD TREATMENT

Low Dose Applications (< 1 kGy)
- **Phytosanitary** Insect disinfection (grains, papayas, mangoes, avocados…)
- **Sprouting Inhibition** (potatoes, onions, garlic…)
- **Delaying of maturation, parasite disinfection**

Medium Dose Applications (1 to 10 kGy)
- **Control of foodborne pathogens** (beef, eggs, crab meat, oysters…)
- **Shelf-life extension** (chicken, pork, low fat fish, strawberries, mushrooms…)
- **Spice irradiation**

High Dose Applications (> 10 kGy)
- **Food sterilisation** (meat, poultry, seafood…)

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RADIOGRAPHY

- dynamically inspecting jet engines
- X-ray screening of cargo containers
- inspecting concrete structure integrity
- inspecting castings
- reverse engineering CT studies
- nuclear waste inspection
- border control

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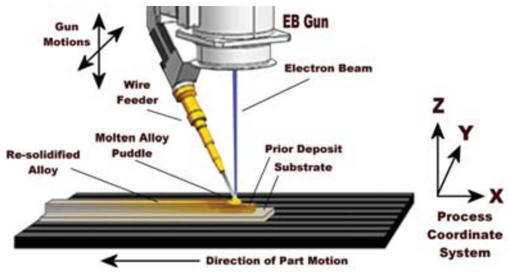
WELDING AND CUTTING



Not formation of reactive species is important, but well-defined electron beam heat deposition

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SYNCHROTRON RADIATION in MEDICINE and INDUSTRY

- continuous X-ray spectrum of high intensity
- strong concentration in the horizontal plane
- small source size and low divergence

⇩

INDUSTRIAL
- X-ray lithography for microelectronics
- deep X-ray lithography for micromachining

MEDICAL
- digital substraction angiography

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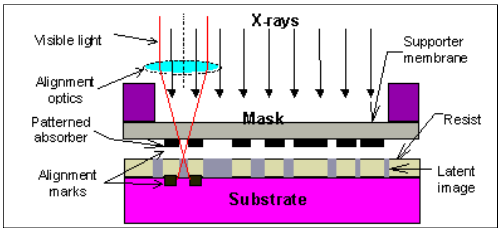
X-ray lithography for microelectronics

the SMALLER the wavelength the better the resolution

↳ X-ray lithography



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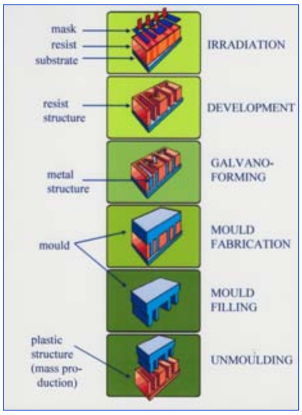
Deep X-ray lithography for micromachining



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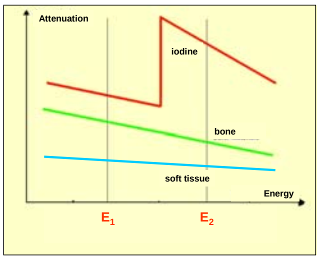
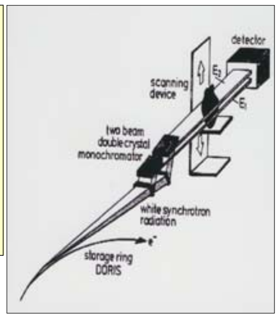
Digital substraction angiography



Monochromatic X-rays



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Basic design considerations

Critical wavelength:
- 1 nm — X-ray lithography
- 0,2 nm — deep X-ray lithography
- 0,0037 nm — digital substraction angiography

Photon flux: 2.10^{11} - 2.10^{12} ph/sec-mm^2

Required radiation at the lowest price

⇩

2nd generation

COMPACT SR FACILITIES ⟺ Research SR facilities

DESIGN CRITERIA
- 0.7 – 3 GeV range
- high photon flux
- small size
- low investment and operating cost
- not too complex
- easy to operate
- applications define ring parameters

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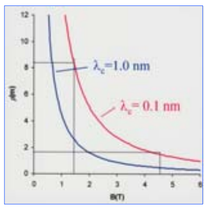
1. MAGNETS

COMPACTNESS

Normal-conducting ↔ **superconducting magnets ?**

Normal-conducting:
- simplify existing storage ring design
- remove some quadrupoles
- dimensions ↓

Superconducting magnets:
- unusual storage ring design
- new optical schemes
- dimensions ↓↓



$$\lambda_c = \frac{20.7}{\rho^2(\mathrm{m})B^3(\mathrm{T})}$$

Normal conducting	1,5 T	
Superconducting	4,5 T	ρ/5

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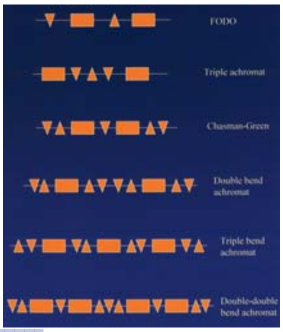
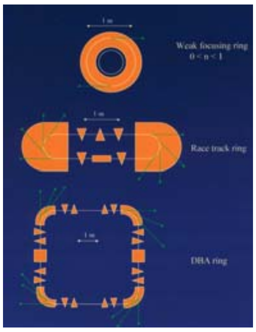
2. LATTICES

IRON MAGNET LATTICES



SUPERCONDUCTING LATTICES



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3. INJECTION at LOW ENERGY

Accumulation of high currents in SR facilities:
- injection of bunch
- phase space shrinks during damping time
- following bunch injected

Low energy: preaccelerator space and cost ↓↓

- weak radiation damping efficiency — damping time ~ 1 / E^3 ≈ lifetime
- scattering with gas atoms — lifetime ↓↓
- Touscheck scattering: mutual interaction of electrons in bunch — lifetime ↓

LINACS
MICROTRONS

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ANKA

- Energy — 2.5 GeV
- Stored current — 400 mA
- Bending radius — 5.56 m
- Magnets — 8 normal conducting 22.5° — 4 cells of 2 x DBA
- Critical wavelength — 0.2 m
- Magnetic field — 1.5 T
- Nb of beamports — 11
- Diameter ring — ∅ 35 m
- Injector — 500 MeV booster synchrotron — 53 MeV microtron

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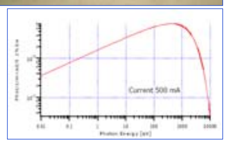
HELIOS

HELIOS 1 — IBM East Fishkill
HELIOS 2 — Singapore

- Energy — 700 MeV
- Stored current — 620 mA
- Bending radius — 0.52 m
- Magnets — 2 superconducting 180°
- Critical wavelength — 0.84 m
- Magnetic field — 4.5 T
- Nb of beamports — 20
- Dimensions — 6 m x 2m
- Injector — 200 MeV linac (HELIOS 1)
  100 MeV microtron (HELIOS 2)



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