GHENT UNIVERSITY

European Commission

juas
Joint Universities Accelerator School

LOW-ENERGY ELECTRON ACCELERATORS

Applications in medicine and industry
PART 3

Wim Mondelaers

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

Joint Research Centre

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

BEAM POWER = ENERGY x INTENSITY

<u>Energy</u>

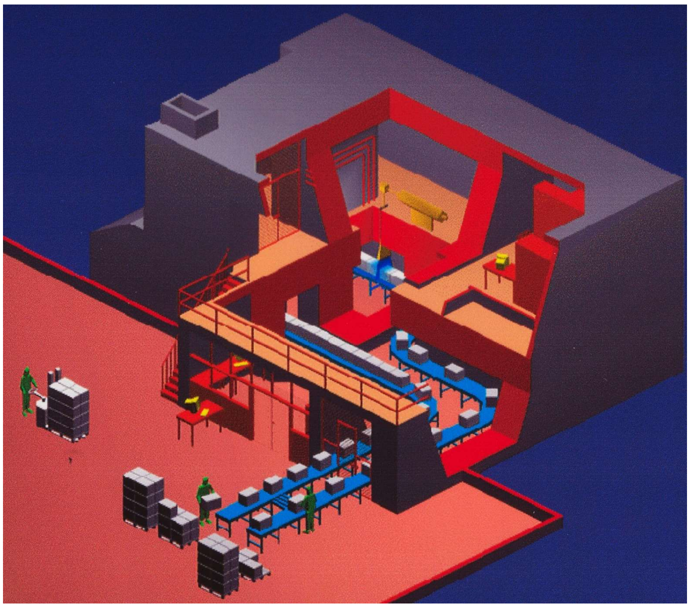
< 10 MeV electrons
< 5 MeV photons

~ penetration depth

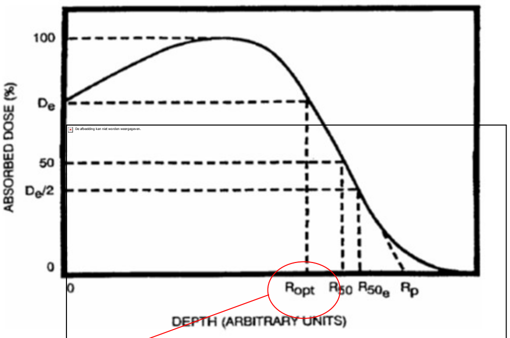
DOSE RATE
⇓
INTENSITY

150 KW

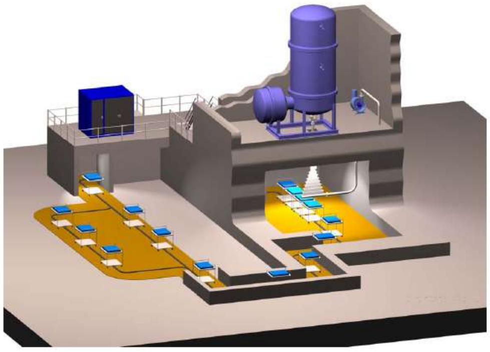
5 MeV / 30 mA
0.5 MeV / 300 mA



Electron range in radiation processing



R_{opt} : exit dose equals entrance dose



R_{opt} = optimal range in g/cm^2
V = energy of electrons in MeV

$$\boxed{R_{opt} = 0{,}404V - 0{,}161}$$

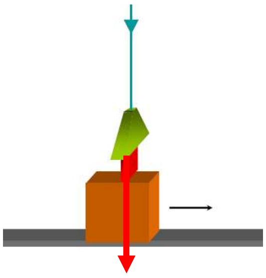
$$R_{opt}(cm) = R_{opt}(g/cm^2)/\rho(g/cm^3)$$

Throughput in radiation processing (electron and X-ray mode)

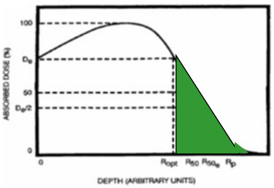
Mass throughput

$$\frac{M}{T} = F(e)F(i)\frac{P}{D(ave)}$$

M = mass in kg
T = time in seconds
P = emitted radiation power in kW
D(ave) = average absobed dose on kGy



F(i) = fraction of emitted beam current intercepted by material



F(e) = fraction of incident electron energy absorbed by material

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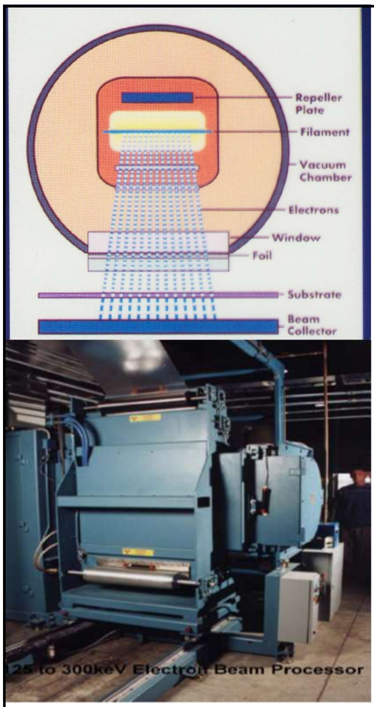
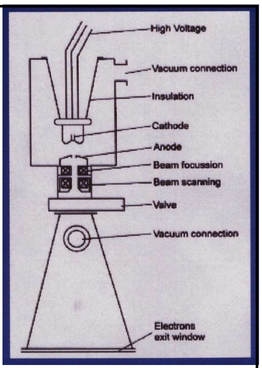


Energy range 0.1 - 0.5 MeV

Single-stage machines

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



SCANNING TYPE

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

BROAD BEAM

Energy range 0.5 - 5 MeV

Multi-stage machines

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

COCKROFT-WALTON

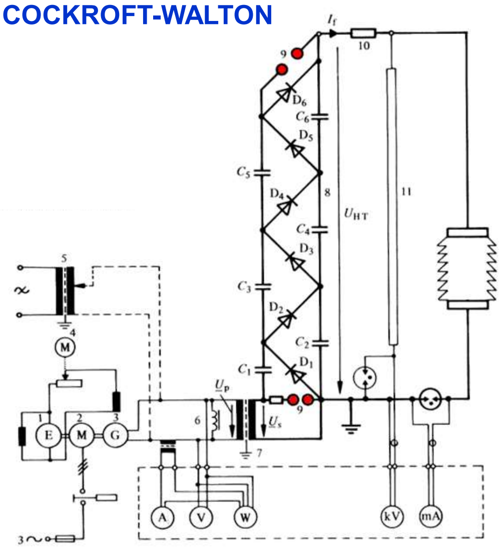
INSULATED-CORE TRANSFORMER

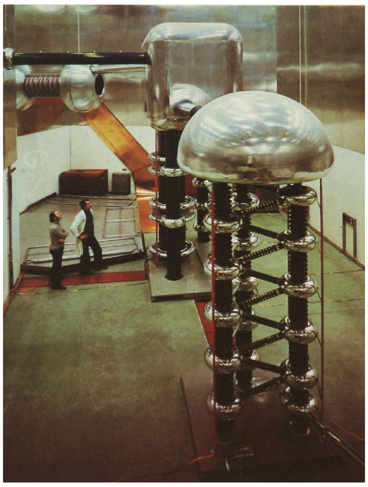
DYNAMITRON

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

Energy range 0.5 - 5 MeV

COCKROFT-WALTON

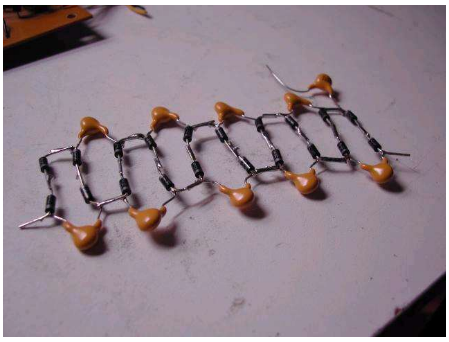




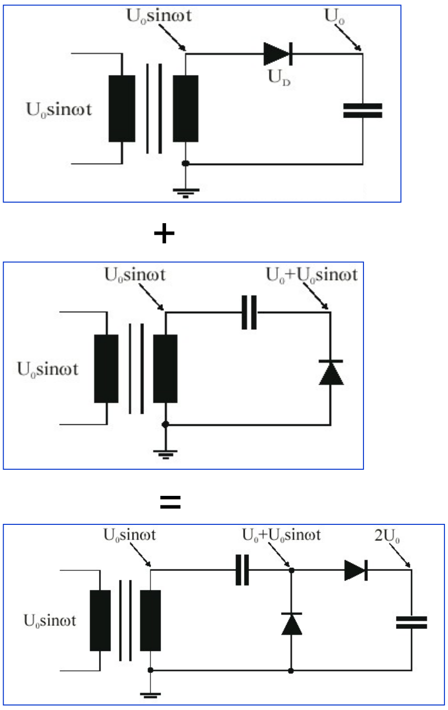
Greinacher cascade generator

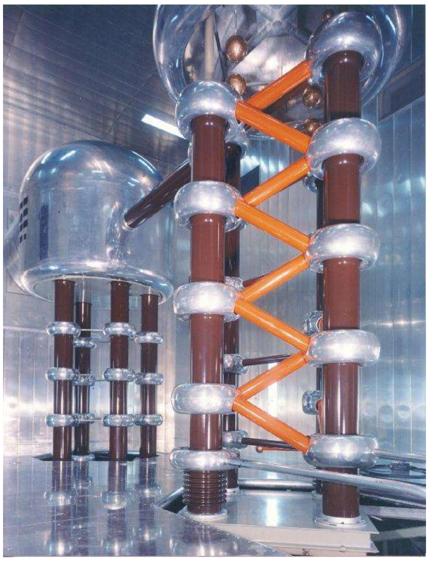
COCKROFT-WALTON

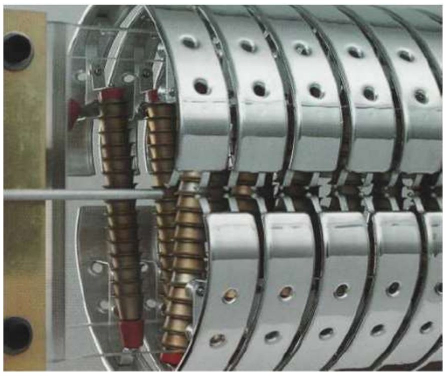
Greinacher circuit or voltage multiplier



$$U_{\max} = 2nU - \frac{2\pi}{\omega C}\left(\frac{2}{3}n^3 + \frac{1}{4}n^2 + \frac{1}{12}n\right)$$

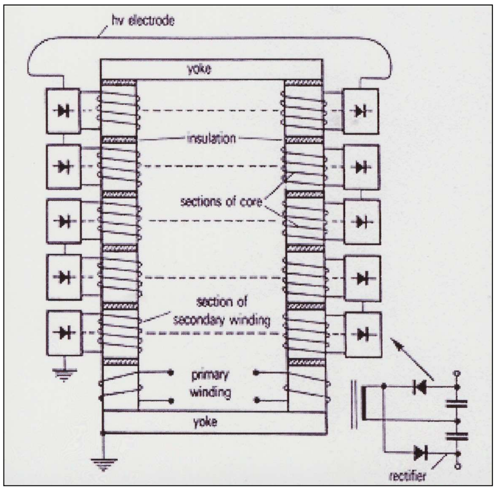






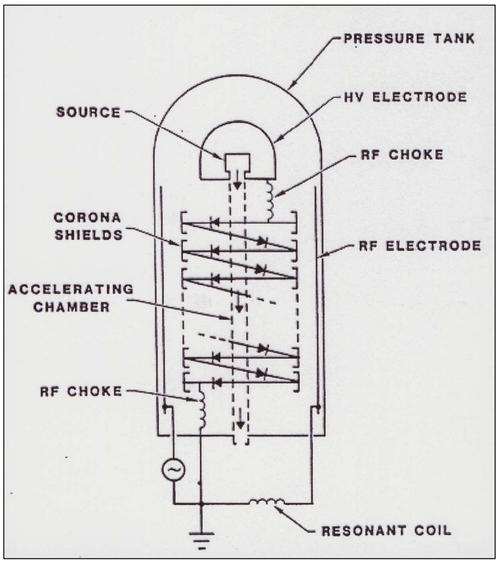
Energy range 0.5 - 5 MeV

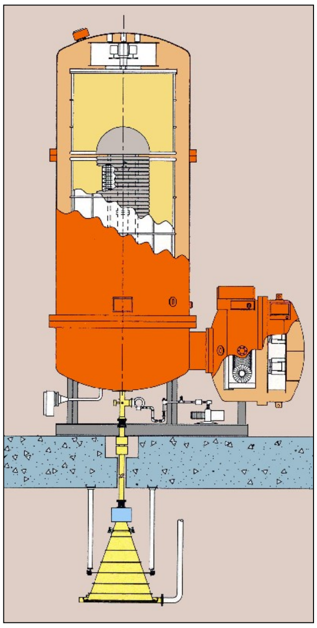
INSULATED-CORE TRANSFORMER



Energy range 0.5 - 5 MeV

DYNAMITRON





DYNAMITRON

Energy range 5 - 10 MeV

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

APPLICATIONS:

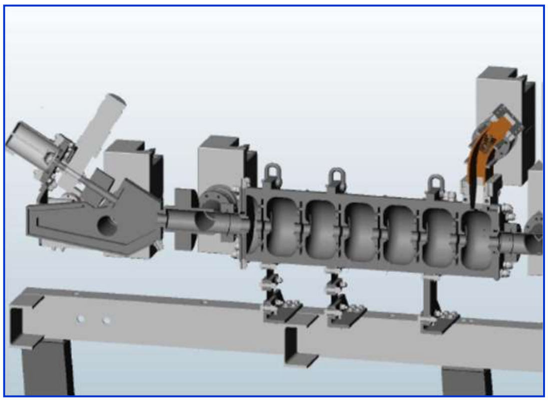
- < 5 MeV applications
- medical sterilisation
- food processing
- polymer crosslinking, grafting, degradation

Energy range 5 - 10 MeV

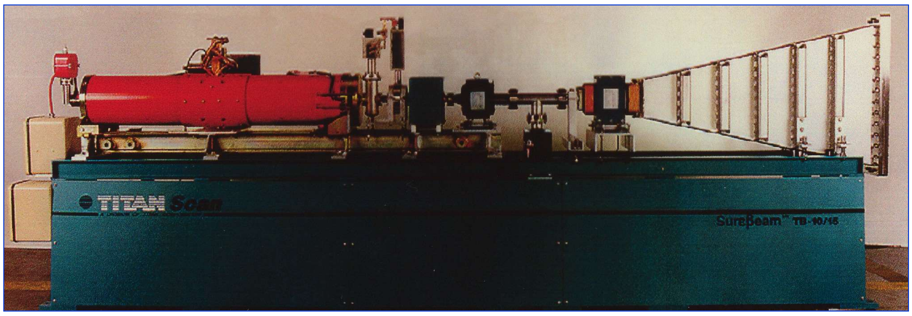
$$V = \sqrt{(1-e^{-2\tau})P_0R_0L} - \frac{R_0LI}{2}\left[1 - 2\tau\frac{e^{-2\tau}}{1-e^{-2\tau}}\right]$$

BEAM POWER : 50 kW

SHUNT IMPEDANCE ↑↑↑



LINAC

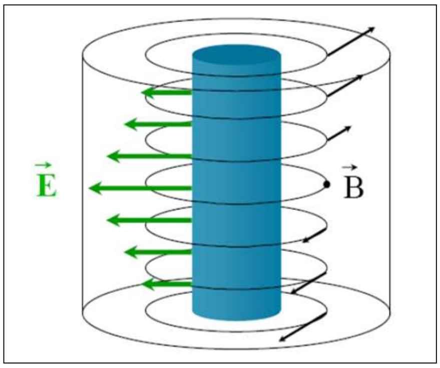


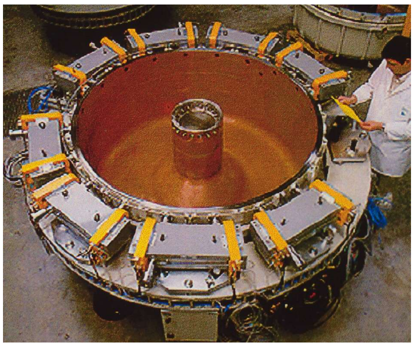
Energy range 5 - 10 MeV

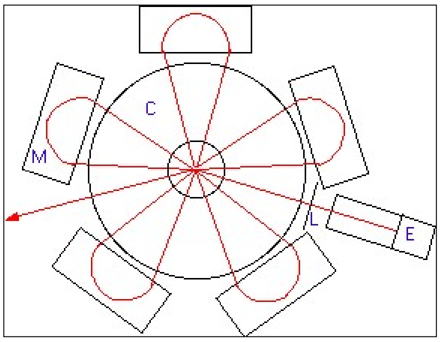
RHODOTRON

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

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

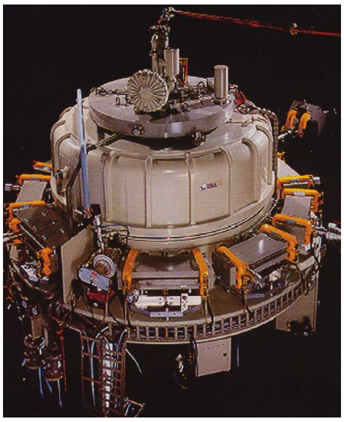


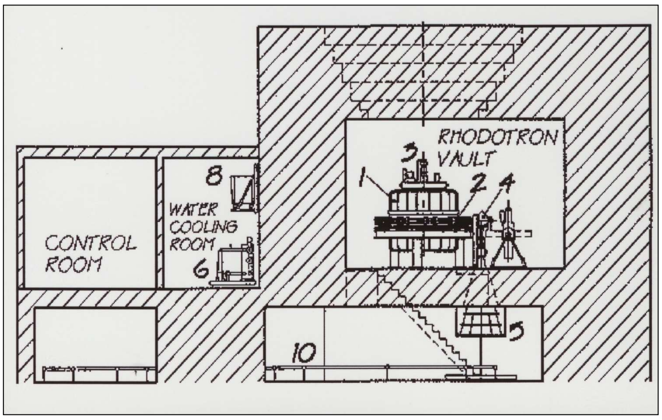




Energy range 5 - 10 MeV

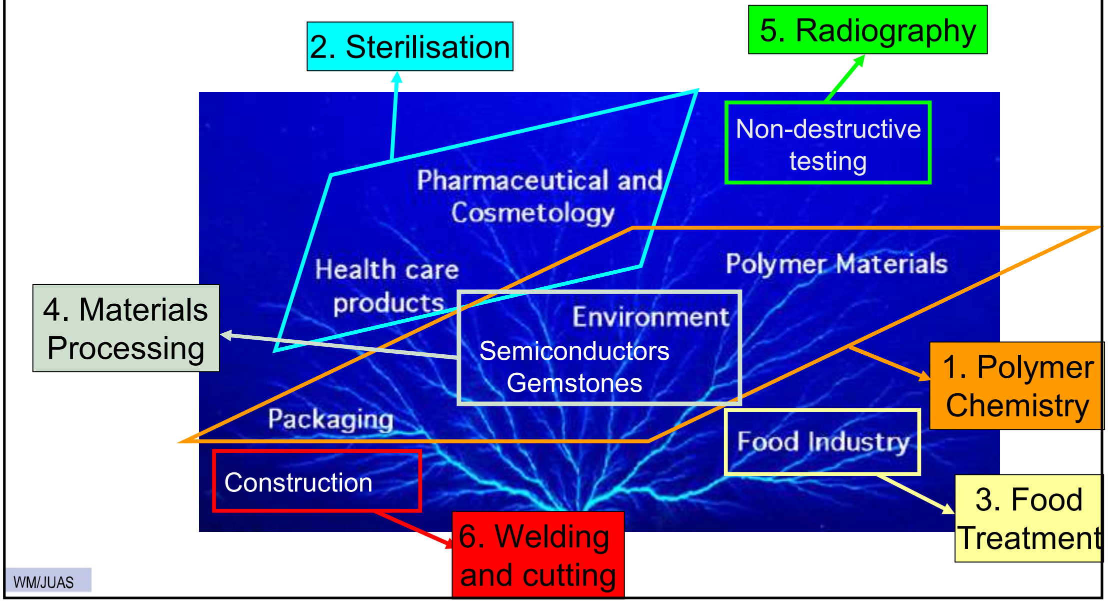
RHODOTRON





High-power electron beams : up to 1 MW
10 MeV / 100 mA

INDUSTRIAL APPLICATIONS of ELECTRONS and BREMSSTRAHLUNG



2. Sterilisation

5. Radiography

Non-destructive testing

Pharmaceutical and Cosmetology

Health care products

Polymer Materials

4. Materials Processing

Environment

Semiconductors

Gemstones

1. Polymer Chemistry

Packaging

Food Industry

Construction

3. Food Treatment

6. Welding and cutting

INDUSTRIAL APPLICATIONS
of ELECTRONS and BREMSSTRAHLUNG

1. POLYMER CHEMISTRY
   - → 1.1 *crosslinking*
   - → 1.2 *grafting*
   - → 1.3 *curing*
   - → 1.4 *degradation*
2. STERILISATION
3. FOOD TREATMENT
4. MATERIALS PROCESSING
5. RADIOGRAPHY
6. WELDING AND CUTTING

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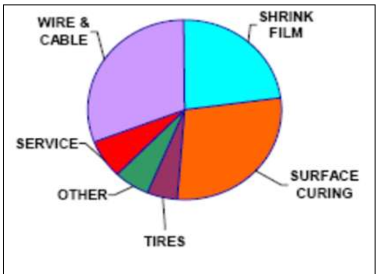
1. POLYMER CHEMISTRY

radiation → **free radicals**

→ **break bonds**

NEW polymer structures
with NEW properties

- crosslinking of cable insulation
- polymerisation of films
- curing of coatings



Total of $50 billion per year

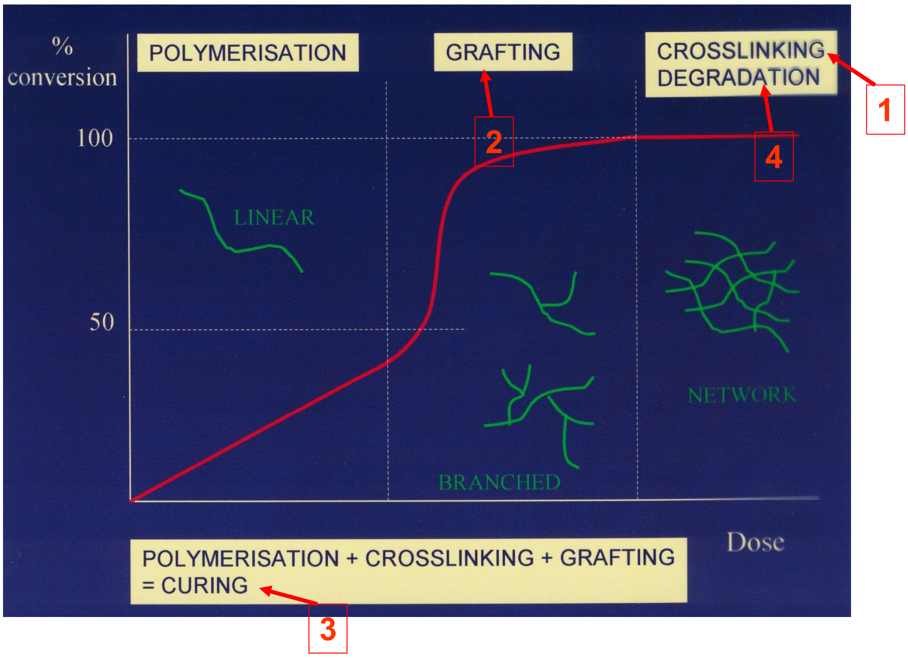
ADVANTAGES

1. High reactivity of species
   - **→ low temperature**
   - **→ no catalysts - high purity**
   - **→ no toxic or carcinogenic agents**

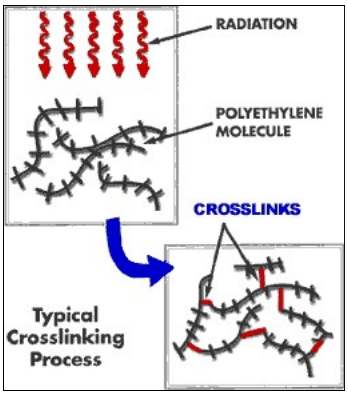
2. Reaction rate ~ dose rate

3. Chemical binding of incompatible substances

1. POLYMER CHEMISTRY : irradiation of monomers



1.1 CROSSLINKING



Linear molecule → 3D structure
e.g. polyethylene

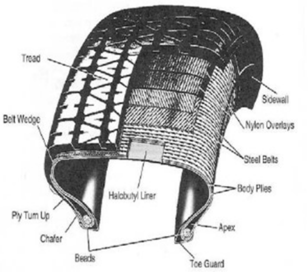
⇩

≠ 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

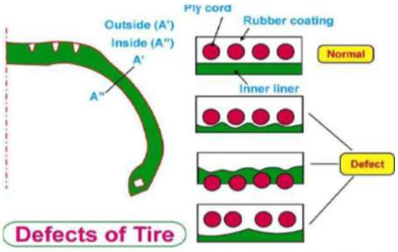
EXAMPLE : **Pre-vulcanisation of tires**



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 friction



Defects of Tire

Radiation Processing Avoids These

EXAMPLE : **Synthesis of biomaterials**

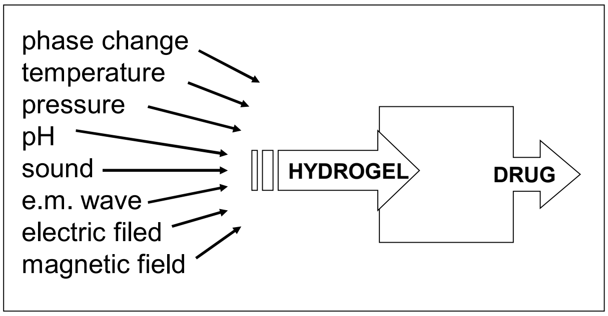
HYDROGELS =
crosslinked macromolecular networks swollen in water

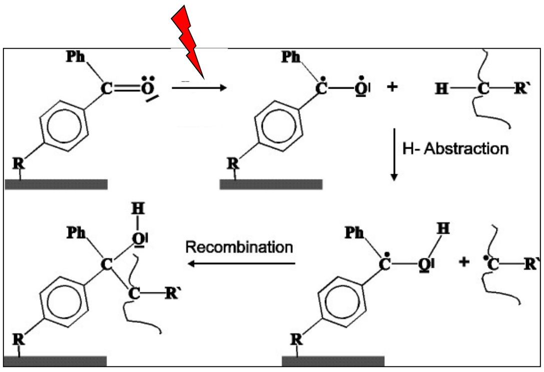
- rubbery structure
- substantial water content
- ~ soft living tissue → BIOCOMPATIBLE
- porous network → BIOFUNCTIONAL

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

↓

constant release
signal responsive





1.2 GRAFTING

Polymer backbone + monomer

⇩

≠ surface properties

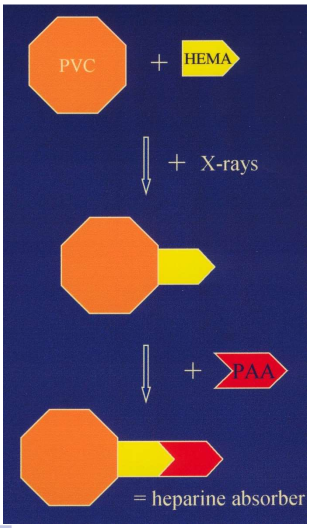
- biocompatibility
- adhesion
- permeability
- wettability
- chemical resistance
- chemical compatibility
- printability
- hydrophilic / phobic quantities
- functionalisation
- mechanical properties

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

EXAMPLE : **Immobilisation of bioactive agents**

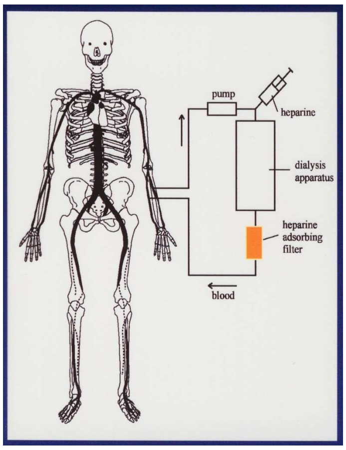
Grafting of biofunctional groups on polymer supports

- HEPARINE FILTER

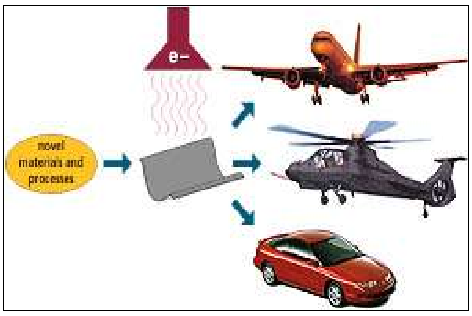


Hemodyalysis of uremic patients
blood + artificial surfaces → coagulation

heparine adsorbing filters



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



1.3 CURING

Polymerisation + crosslinking + grafting

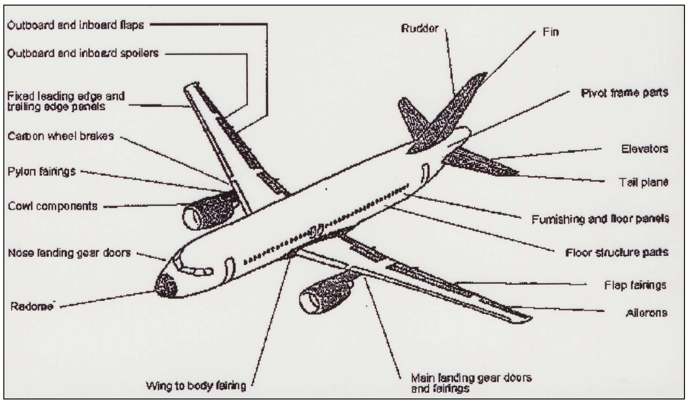
on SURFACES (mainly with electrons)
- antistatic films
- laminates (credits cards, telephone cards)
- offset printing
- door finishing
- parquet coating
- protective films….

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

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

1.4 DEGRADATION

applications of accelerator beams for the environment

- degradation of pollutants
  - liquid effluents treatment: water, industrial or hospital waste, sewage sludge
  - flue gase treatment: SO2 and NOx removal

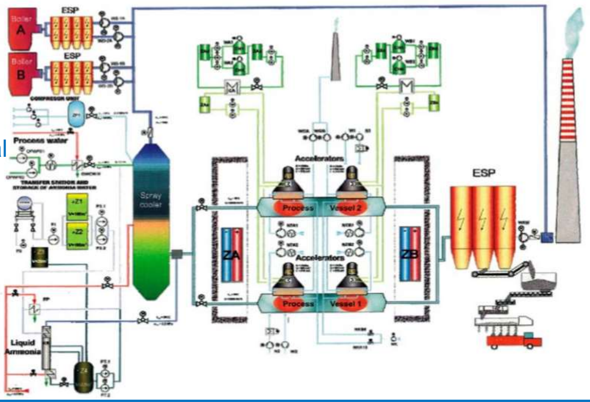
projects in Japan, USA, Germany, China and Poland

Pomorzany EPS, Poland

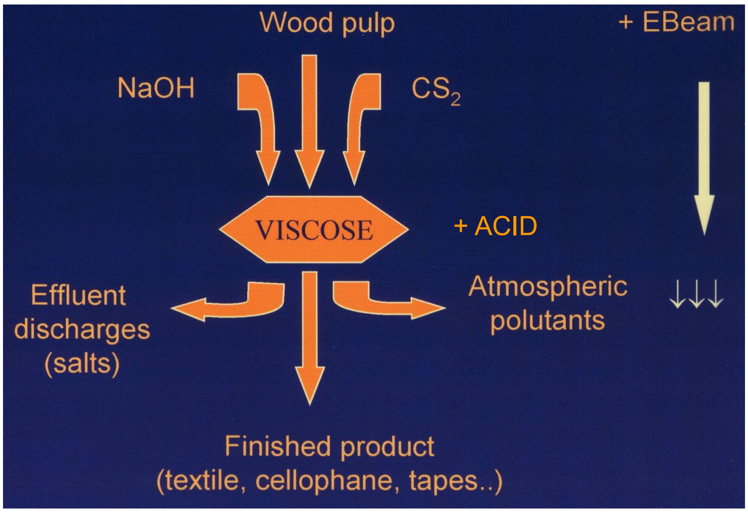
simultaneous SO2 and NOx removal

4 electron accelerators:
700 keV, 260 kW

applied dose: 7–12 kGy



EXAMPLE : **Cellulose in viscose industry**



Wood pulp

+ EBeam

NaOH

CS_2

VISCOSE

+ ACID

Effluent discharges (salts)

Atmospheric polutants

↓↓↓

Finished product
(textile, cellophane, tapes..)

- powdered Teflon molecular weight ↓
  lubricants, high quality inks

INDUSTRIAL APPLICATIONS
of ELECTRONS and BREMSSTRAHLUNG

1. POLYMER CHEMISTRY
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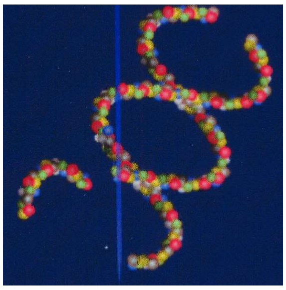
   - → 1.4 *degradation*
2. STERILISATION
3. FOOD TREATMENT
4. MATERIALS PROCESSING
5. RADIOGRAPHY
6. WELDING AND CUTTING



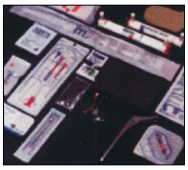
2. STERILISATION

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

3. 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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2. STERILISATION

3. FOOD TREATMENT

→ 4. MATERIALS PROCESSING

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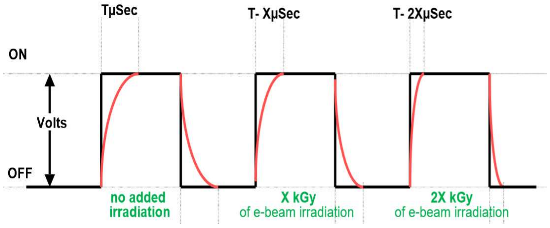
4. MATERIALS PROCESSING

defects in crystals



Improvement of switching speed in semiconductors

- fast recovery diodes, power diodes
- bipolar power transistors, power MOSFETs
- power rectifiers, IGBT's, thyristors silicon-controlled rectifiers

100 kGy

Change of colors in gemstones

1 MGy

topaz

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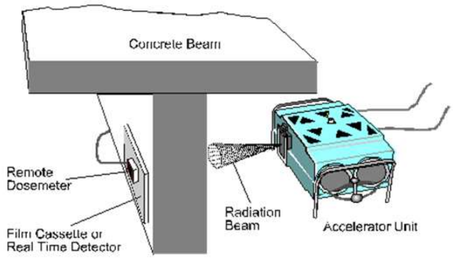
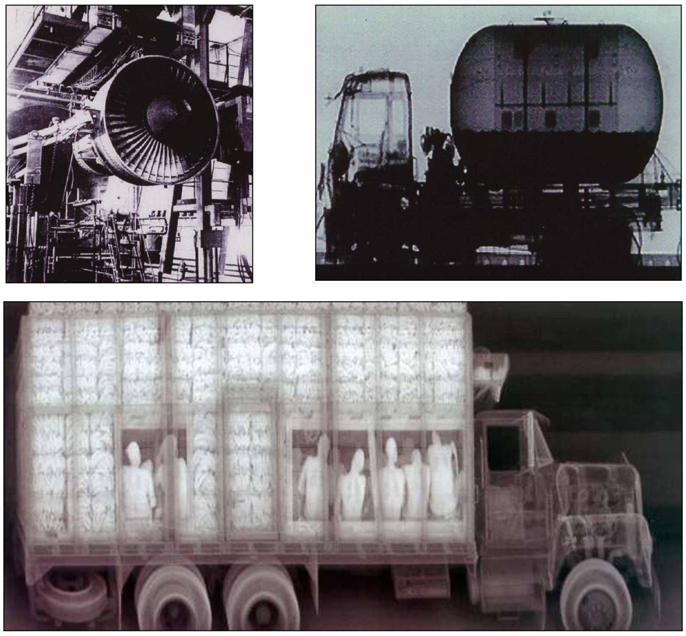
5. RADIOGRAPHY



- 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

5. RADIOGRAPHY



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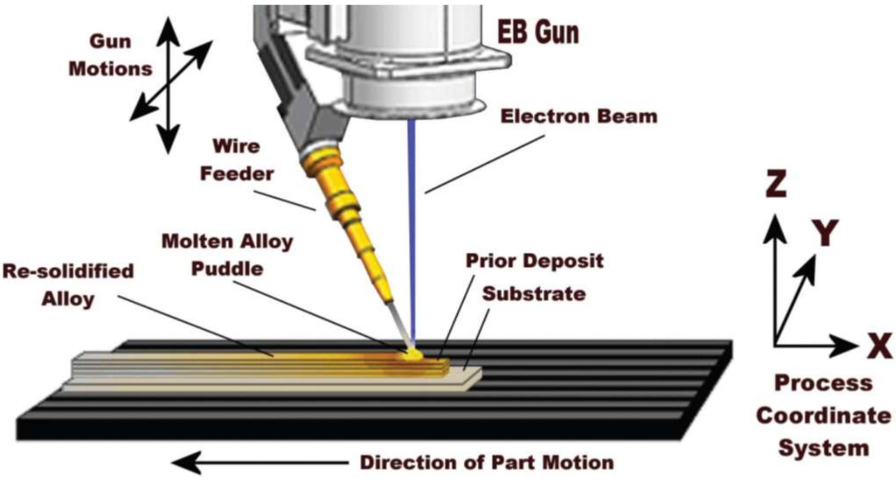
6. WELDING AND CUTTING



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

Low-energy electron machines

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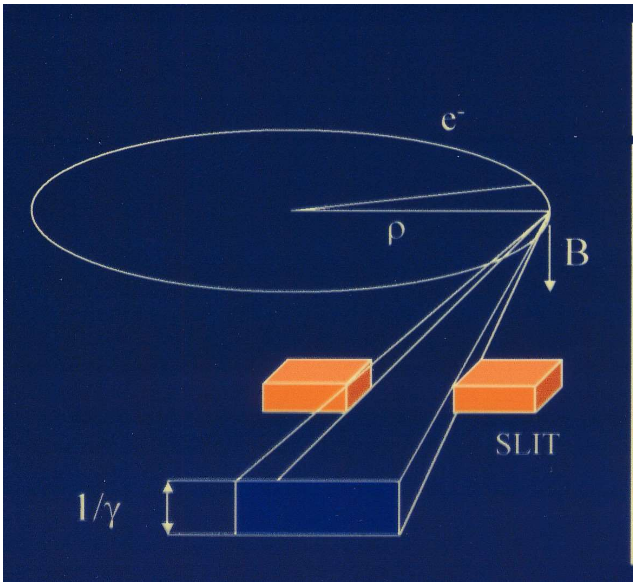
SYNCHROTRON RADIATION



$$U_0(keV) = 88{,}5\frac{E^4(GeV^4)}{\rho(m)}$$

$$\lambda_c(nm) = 0{,}559\frac{\rho(m)}{E^3(GeV)}$$

$$\varepsilon_c(eV) = 2218\frac{E^3(GeV)}{\rho(m)}$$

$$\psi(mrad) = \frac{0{,}546}{E(GeV)}\left(\frac{\lambda}{\lambda_c}\right)^{1/2}$$

$$\cong \frac{1}{\gamma}(\lambda = \lambda_c)$$

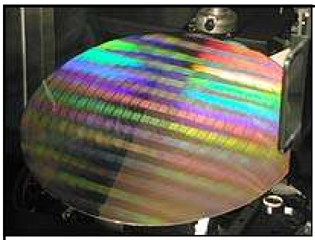
SYNCHROTRON RADIATION

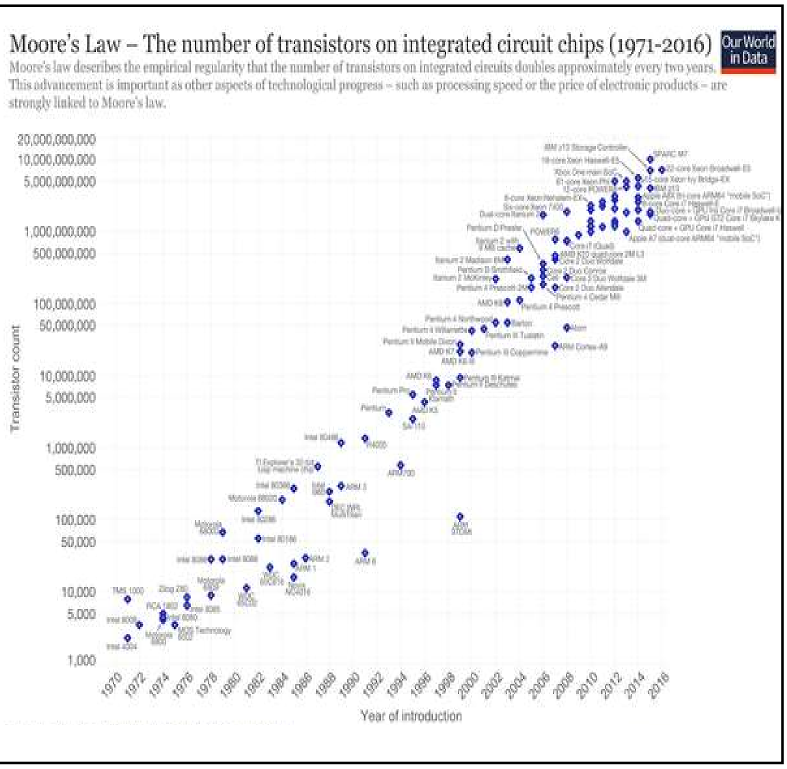
- continuous X-ray spectrum of high intensity
- strong concentration in the horizontal plane
- small source size and low divergence
- high degree of polarisation
- well defined time structure
- precisely calculable radiation characteristics

⇓

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

MEDICAL
- digital substraction angiography





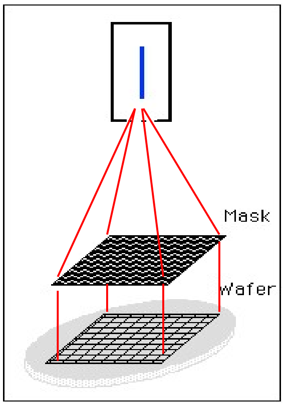
History of computing hardware :

MOORE'S LAW

other aspects of
digital electronic devices:
- processing speed
- memory capacity
- resolution of sensors
- number and size of pixels
  in digital cameras.

Photolithography for microelectronics

Integrated circuits



- illumination of photosensitive wafer
- etching of circuit pattern

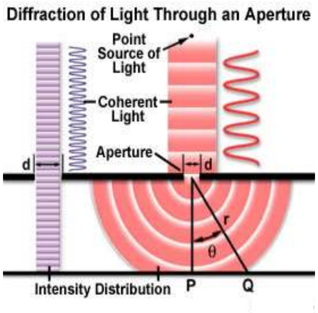
↓

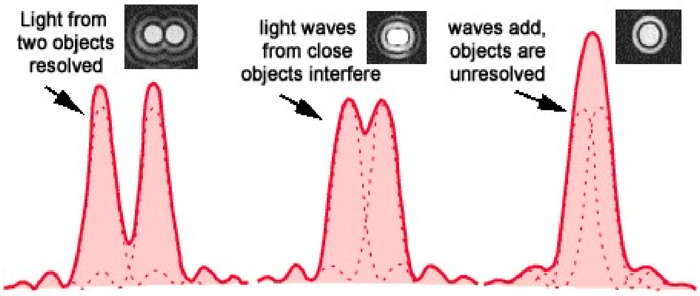
MOORE'S LAW : permanent downsizing

SMALLER dimensions DRAM 2 μm

➡ Optical diffraction effects

Optical diffraction



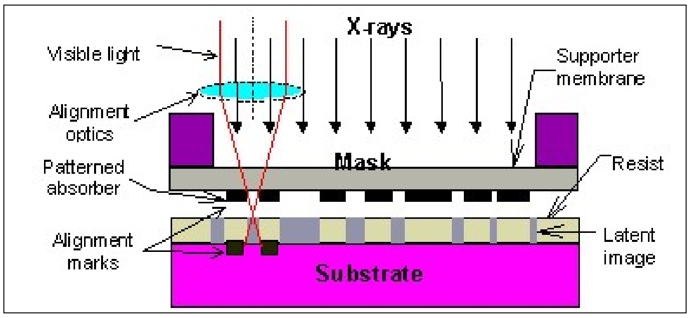


photolithography: no well-defined pattern
resolution limited to 500 nm

the SMALLER the wavelength the better the resolution

X-ray lithography: resolution better than 100 nm

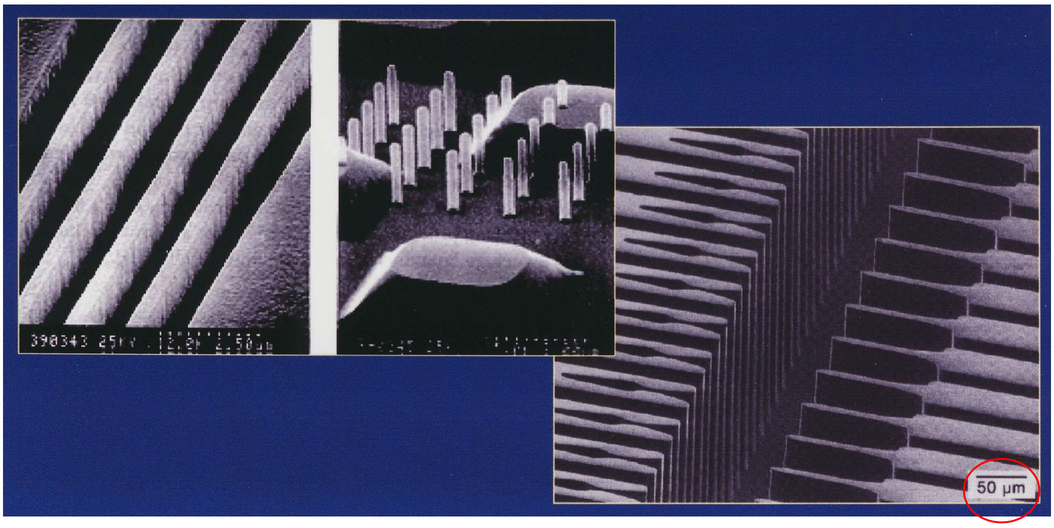
X-ray lithography for microelectronics



Mass production → short illumination times: intense X-ray beams

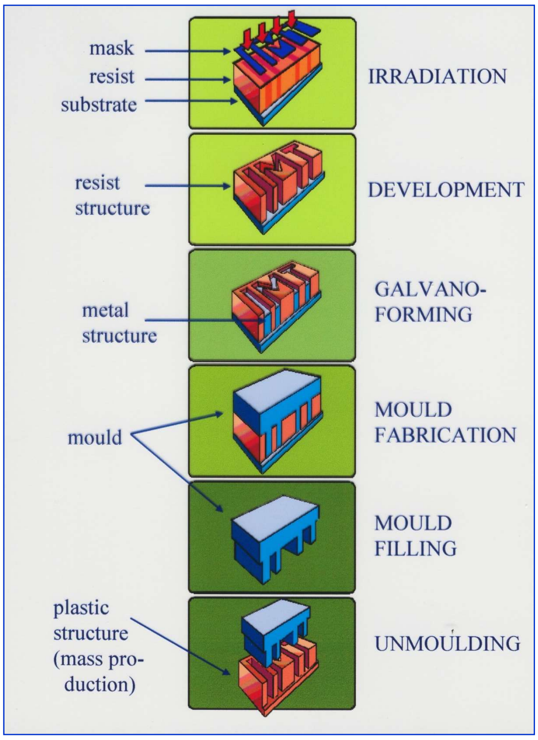
X-ray energy : 1 keV

X-ray lithography for microelectronics



Deep X-ray lithography for micromachining

LIGA process



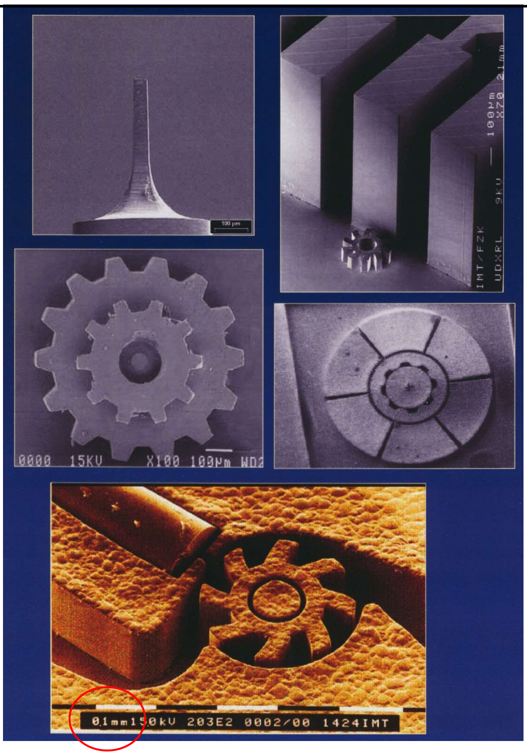
Height / width ~ 100

Side wall accuracy ~ 1 µm

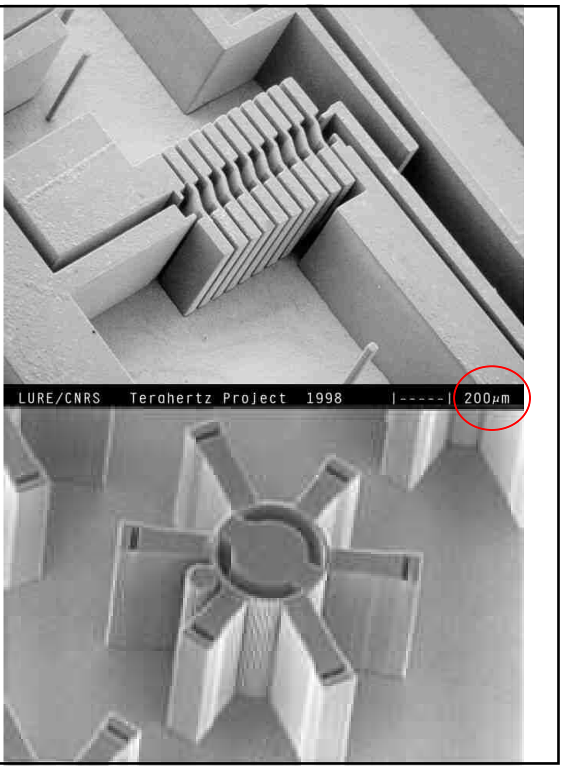
Penetration depth ~ 0.5 mm

X-ray energy : 5 keV

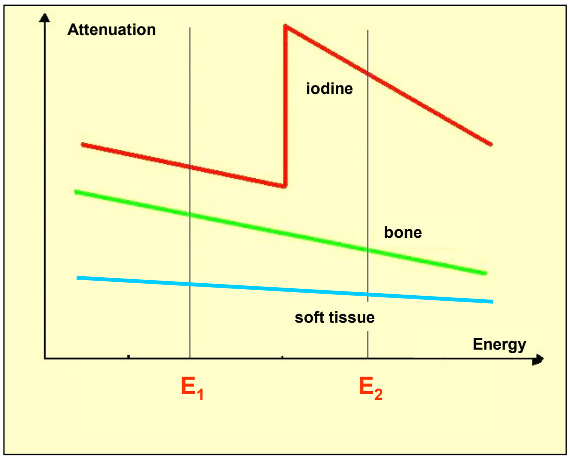
Deep X-ray lithography for micromachining

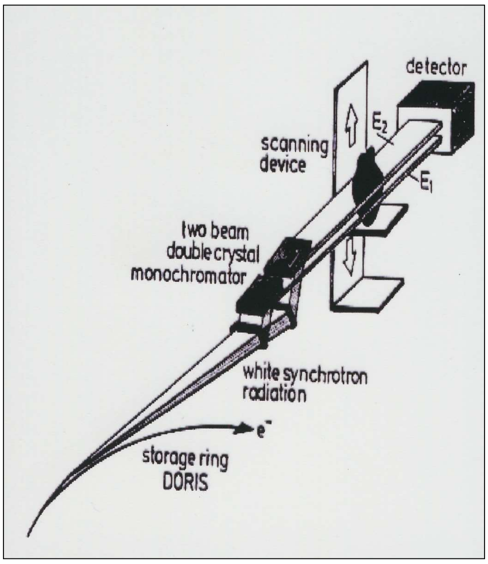


Deep X-ray lithography for micromachining



Digital substraction angiography

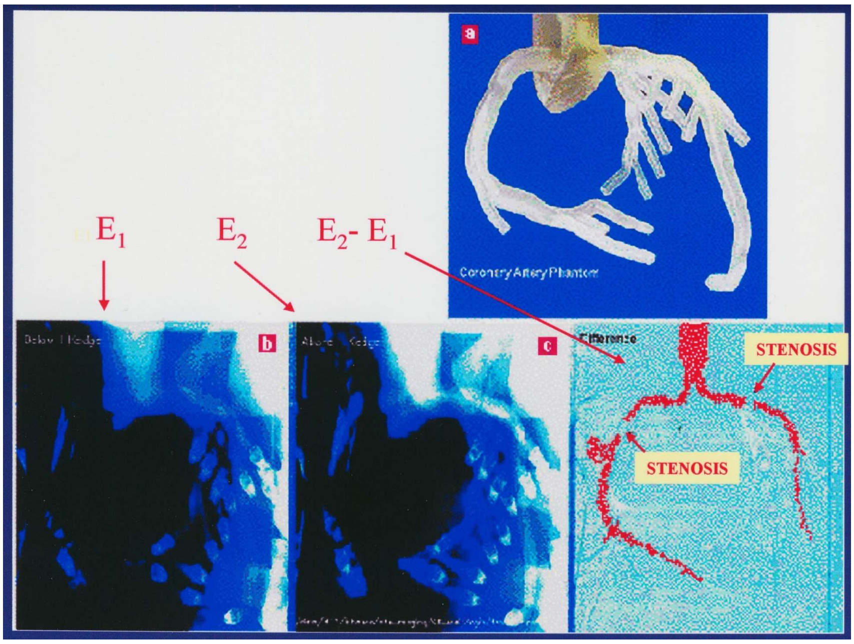




Monochromatic X-rays

X-ray energy : 33 keV

Digital substraction angiography



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

COMPACT SR FACILITIES ⟺ Research SR facilities

2^{nd} generation

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

DESIGN PROBLEMS

1. Normal-conducting ↔ superconducting magnets
2. Unusual magnet lattices
3. Injection of high current at low energies

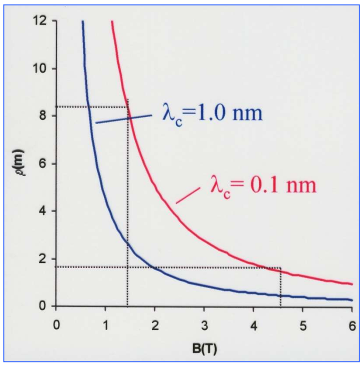
1. MAGNETS

COMPACTNESS

Normal-conducting ↔ **superconducting magnets ?**

- simplify existing storage ring design
- remove some quadrupoles
- dimensions ↓

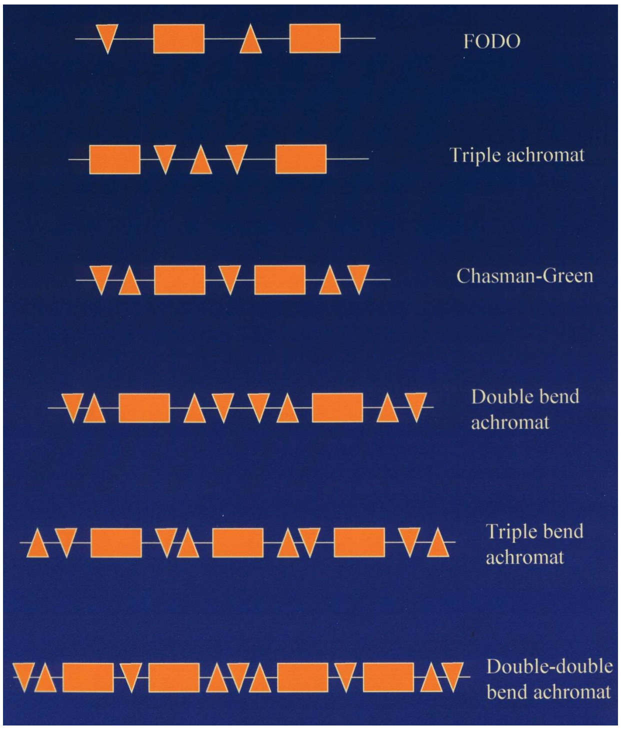
- unusual storage ring design
- new optical schemes
- dimensions ↓ ↓



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

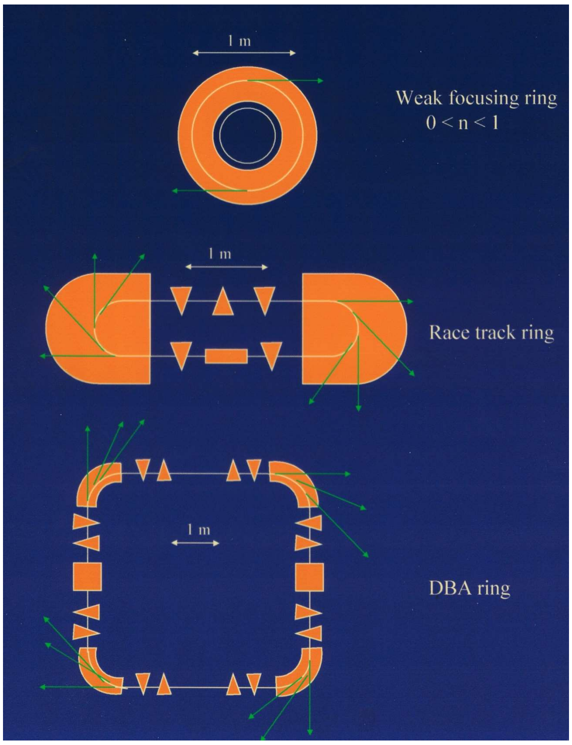
Normal conducting	1,5 T	
Superconducting	4,5 T	ρ/5

2. LATTICES



IRON MAGNET LATTICES

2. LATTICES



SUPERCONDUCTING LATTICES

Compact
↓
number of quadrupoles ↓

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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 ↓↓

↓

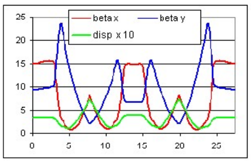
- weak radiation damping efficiency damping time ~ 1 / E^3 ≈ lifetime
- scattering with gas atoms lifetime ↓↓
- Touscheck scattering: mutual interaction of electrons in bunch lifetime ↓

LINACS
MICROTRONS

ANKA

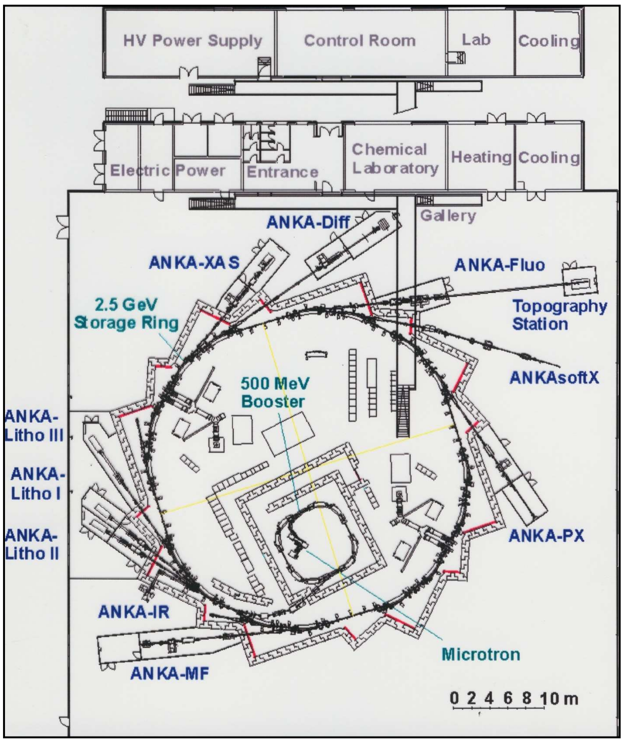
Energy	2.5 GeV
Stored current	400 mA
Bending radius	5.56 m
Magnets	8 normal conducting 22.5° 4 cells of 2 x DBA
Critical wavelength	0.2 m
Magnetic field	1.5 T
Nb of beamports	11
Diameter ring	∅ 35 m
Injector	500 MeV booster synchrotron 53 MeV microtron

ANKA



User Optics

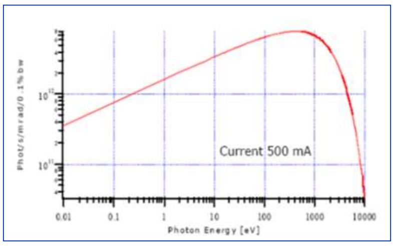
Energy:	2.5 GeV
Circumference:	110.4 m
Emittance:	50 nmrad
nat. Chroma. (h/v):	-10 / -5
nat. Energy Spread:	0.001
Mom. Compaction:	0.009
Tune (h/v):	6.73/ 3.68



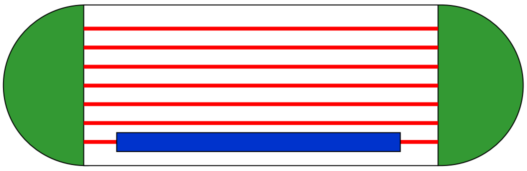
HELIOS

HELIOS 1	IBM East Fishkill
HELIOS 2	Singapore

Energy	700 MeV
Stored current	620 mA
Magnets	2 superconducting 180°
Critical wavelength	0.84 m
Nb of beamports	20
Dimensions	6 m x 2m
Injector	200 MeV linac (HELIOS 1) 100 MeV microtron (HELIOS 2)



Stable motion in HELIOS ring



Stability condition in periodic rings:

$$\boxed{-1 \leq \frac{1}{2}\,\mathrm{traceM} \leq 1}$$

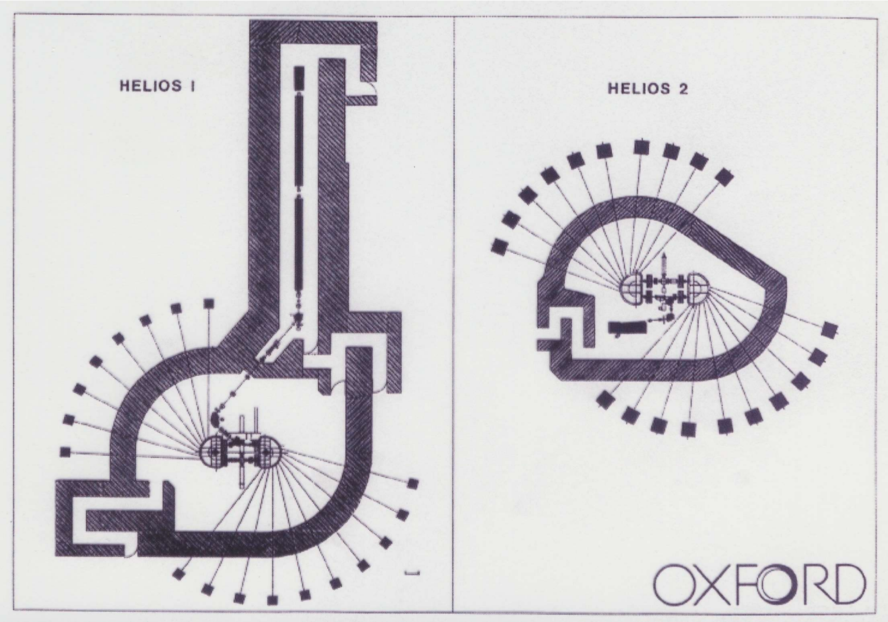
period

$$\mathrm{M} = \begin{pmatrix} \mathrm{m}_{11} & \mathrm{m}_{12} \\ \mathrm{m}_{21} & \mathrm{m}_{22} \end{pmatrix}$$

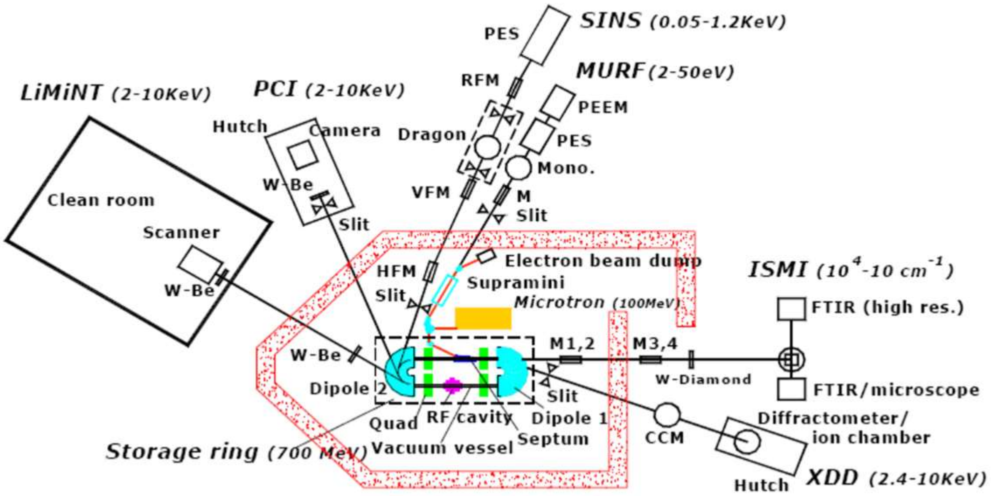
traceM = trace of matrix M, it is equal to the sum of the diagonal elements of matrix M

M is transfer matrix of one period in ring

HELIOS



HELIOS



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

4. Electron accelerators in industry

5. Electron storage rings for medicine and industry