Comparison between eb, gamma, and x-rays facilities for radiation processing

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Erasmus+

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1. Accelerator facilities
2. Gamma facilities
3. X-rays facilities
4. Comparison between eb, gamma, and x-rays facilities (advantages and limitations)

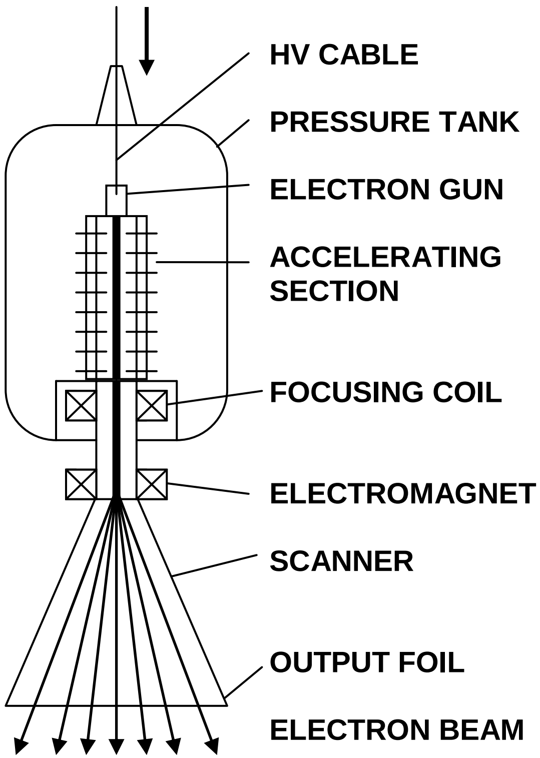
Electron beam or gamma rays?

Do we need X-ray?

What we need?

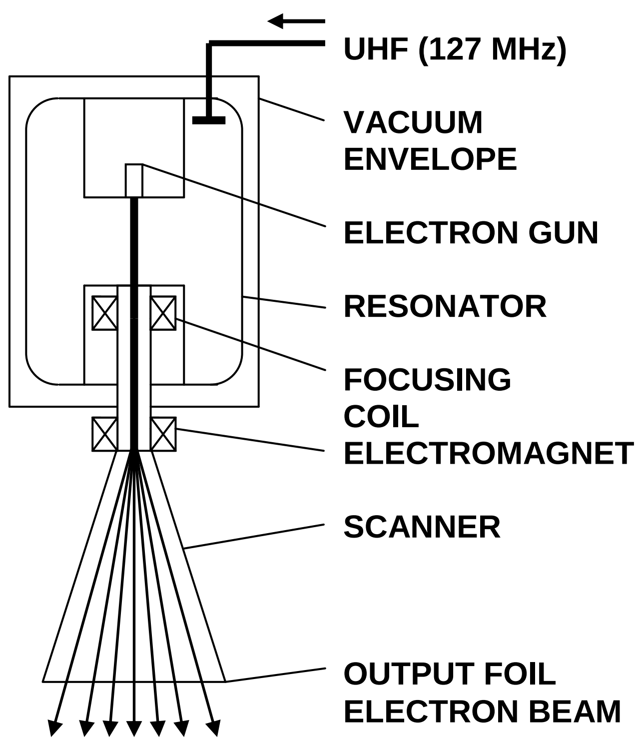
3.1. Accelerator facilities

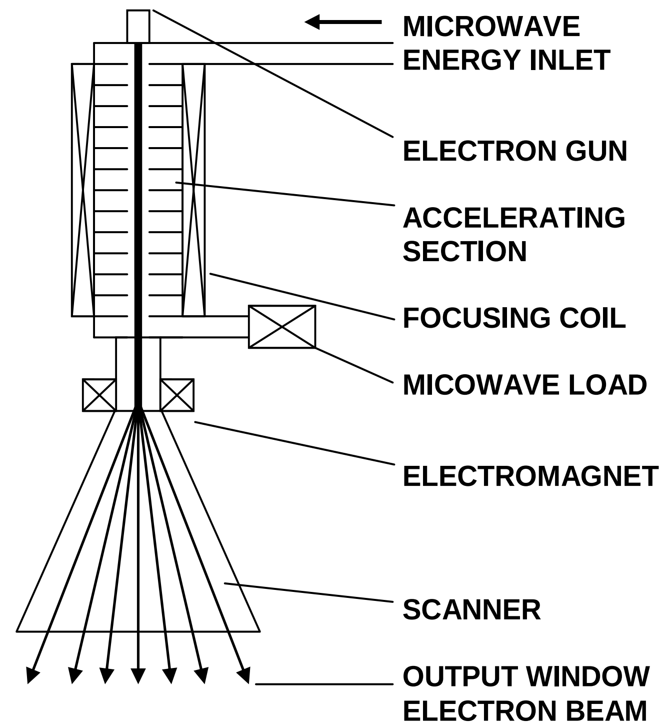
Electron accelerators



DIRECT (TRANSFORMER) ACCELERATORS

SINGLE CAVITY (RESONANCE) ACCELERATORS





LINEAR (MICROWAVE) ACCELERATORS

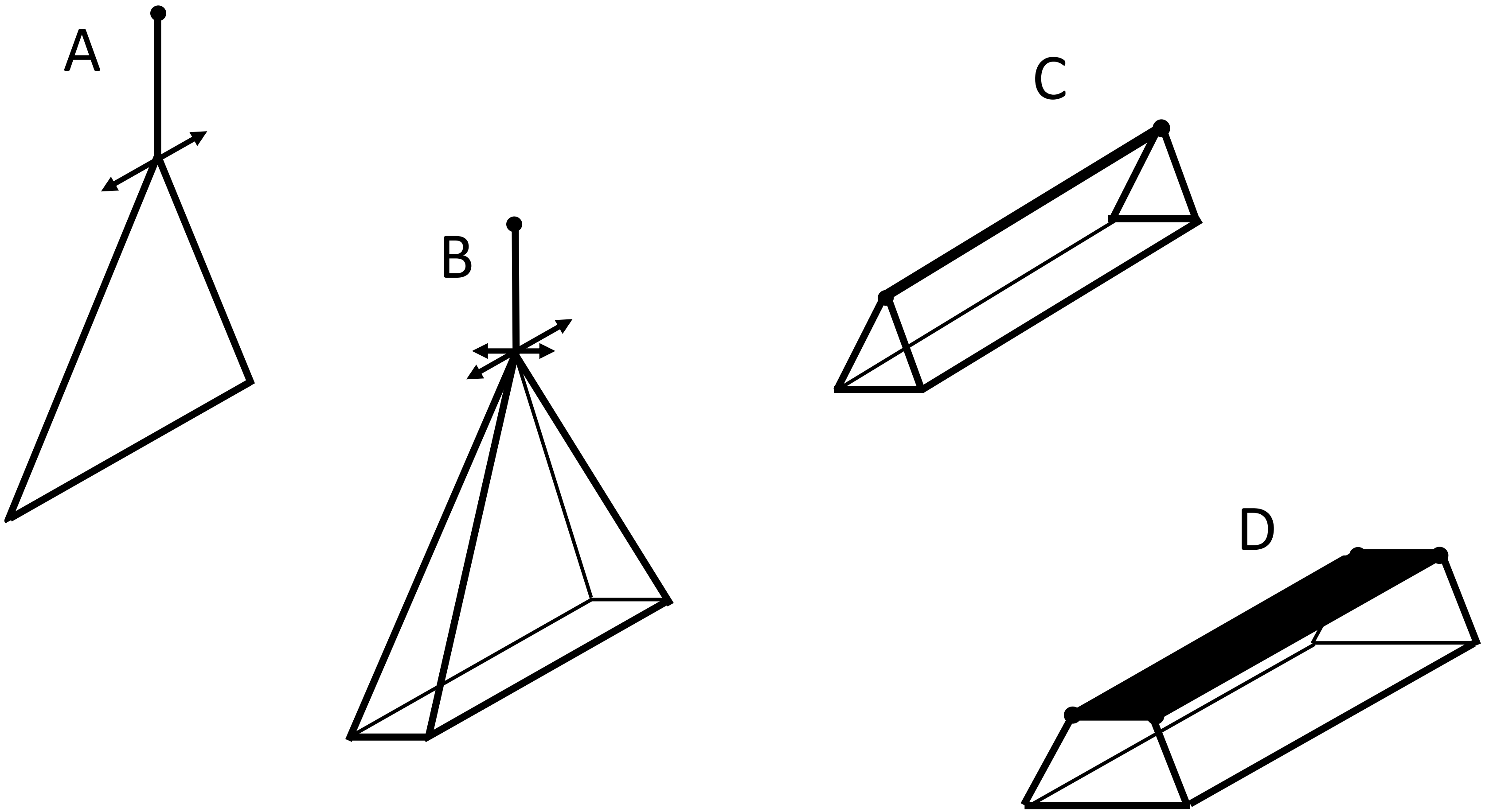
Accelerators for radiation processing

Accelerator type Parameter	Direct DC	UHF 100 - 200 MHz	Linear microwaves 1.3–9.3 GHz
Av. beam current	<1.5 A	<100 mA	<100 mA
Energy range	to 5 MeV	0.3 – 10 MeV	2 – 10 MeV
Beam power	~500 kW	700 kW	100 kW
In future	1 MW	1 MW	200 kW
Electrical eff.	60 – 80 %	20 – 50 %	10 – 20 %

ELECTRON GUNS

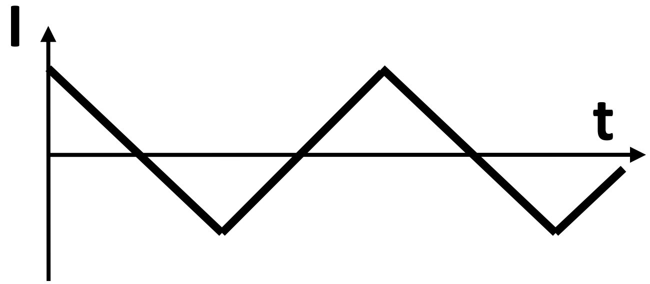
- Accelerators for radiation processing can be divided on two groups depends on cathode construction: point source and linear source instruments.
- A linear cathodes eliminates the need for scanning and offers more uniform dose distribution.
- Linear cathode configuration is suitable for direct accelerators operated at relatively low voltage (80-300 kV).
- Due to high window losses up to 30 - 50% of total beam power is dissipated by cooling system of low energy accelerators.

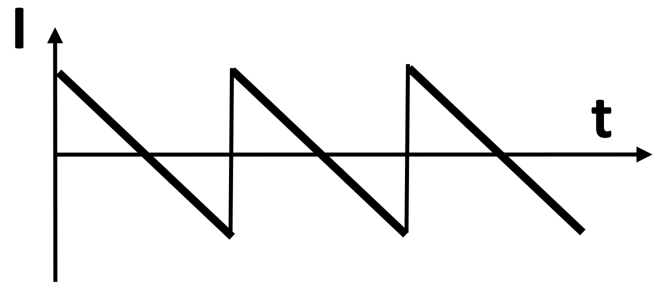
Point and linear source of electrons

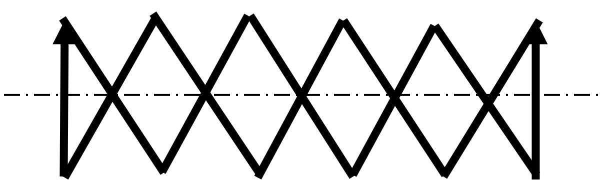


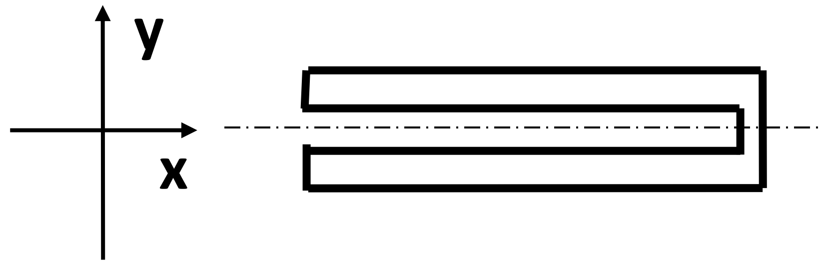
A – point source with linear scan, B – point source with x-y scan, C – linear source, D – linear source with surface cathode

Scanning patterns



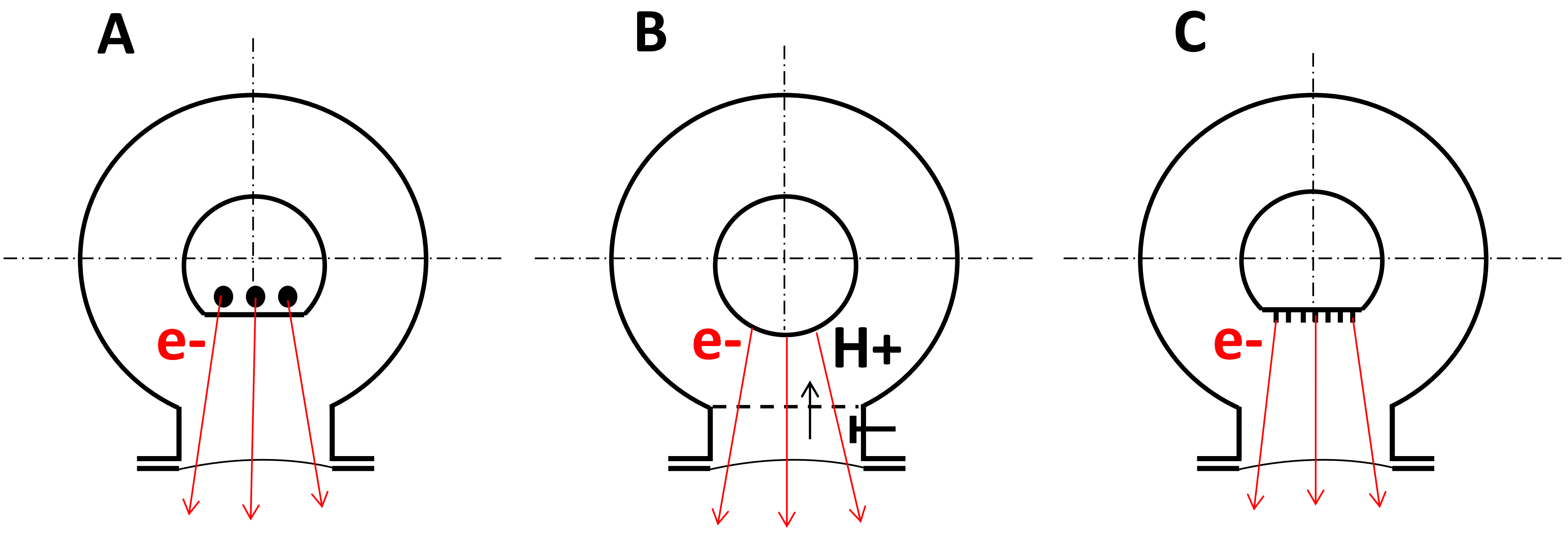






- Accelerators with point source of electrons are designed for higher energy levels.
- The significant advantages of point source accelerator are high flexibility of beam spot formation and beam transport.
- The scanning magnets are used to form required beam dimension on the output of the accelerator.
- Scanned point source accelerators cannot be operated with the current much greater than 1,5 mA/cm due to limited window thermal load.
- Low energy losses (bellow 10%) are characteristic for higher electron energy level but for high beam power energy deposited in widow material is big enough to increase temperature above permissible level.

Low Energy, linear source accelerators
(cross-section)



Different linear cathode construction:
A – heated, B – ion plasma, C – cold emission

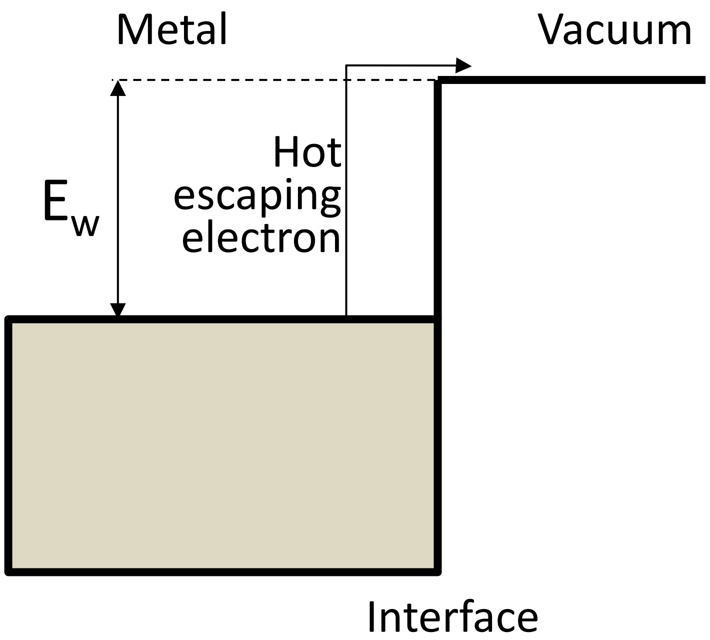
Filament types

Thermonic electron emission

$$J_c = A_c T^2 e^{-E_w/K_B T}$$

$A_c = 120\ A/cm^2K^2$

E_w – work function



Tungsten hairpin

$E_w = 4.5$ eV

$J_c = 3.4\ A/cm^2$ at 2700 K

Operating pressure

10^{-5} mbar

Lanthanum hexaboride (LaB_6)

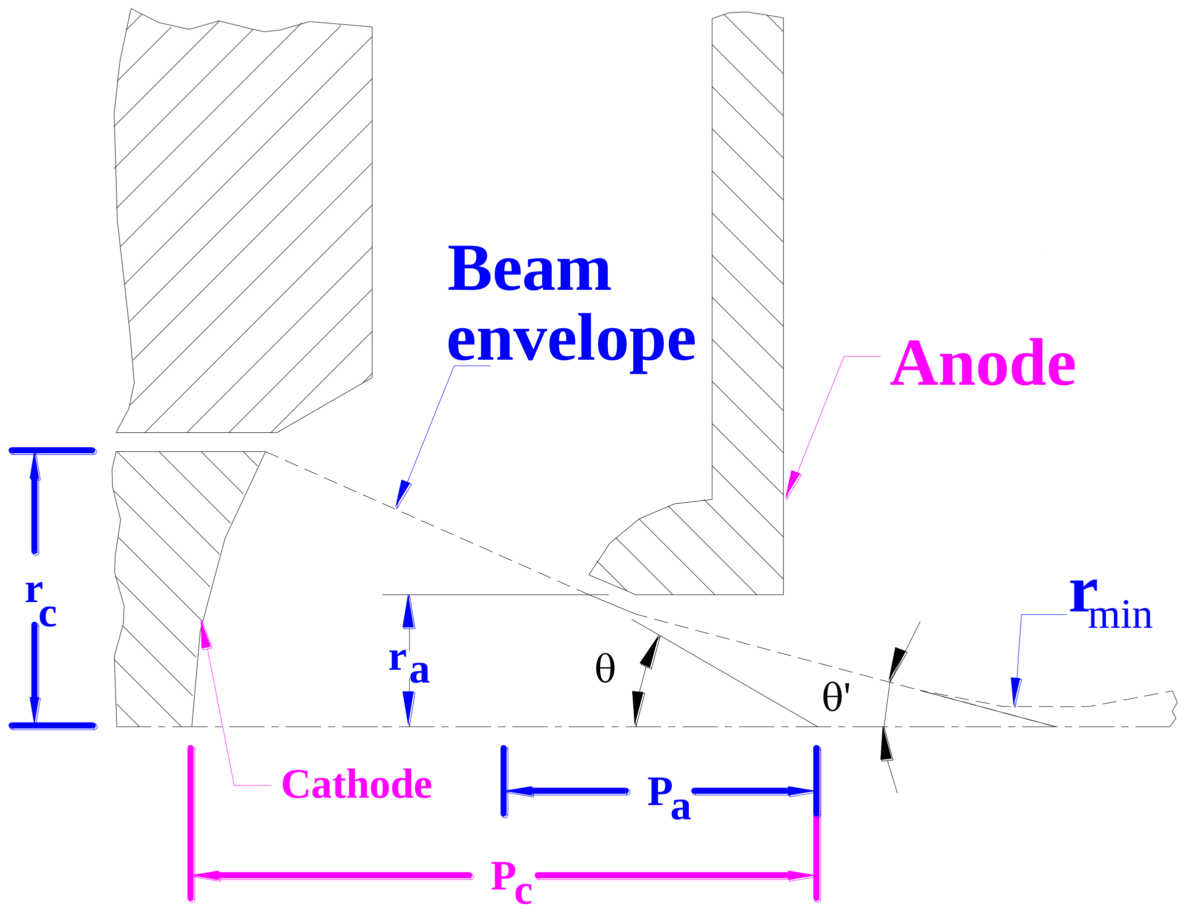
$E_w = 2.5$ eV

$J_c = 40\ A/cm^2$ at 1800 K

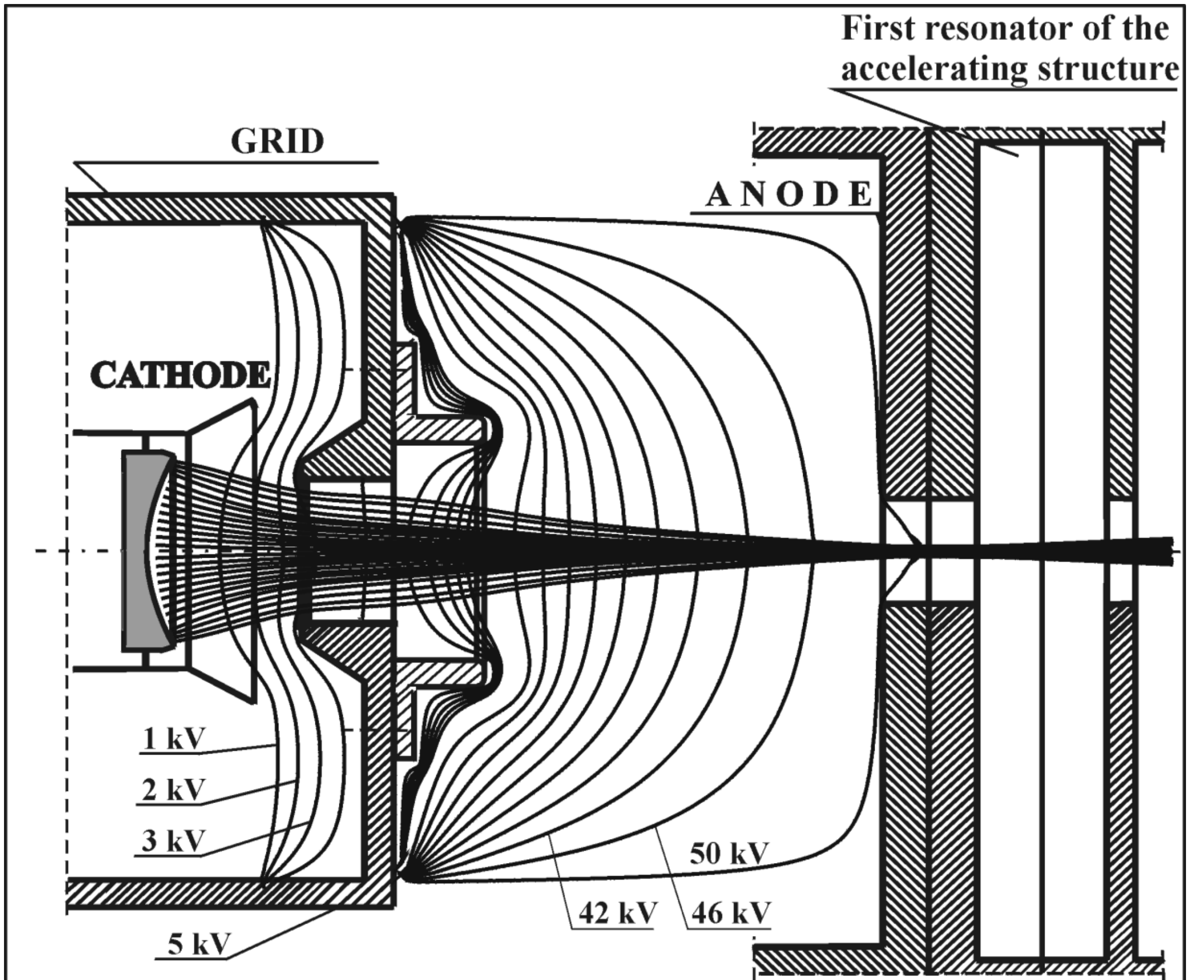
Operating pressure

10^{-6} mbar

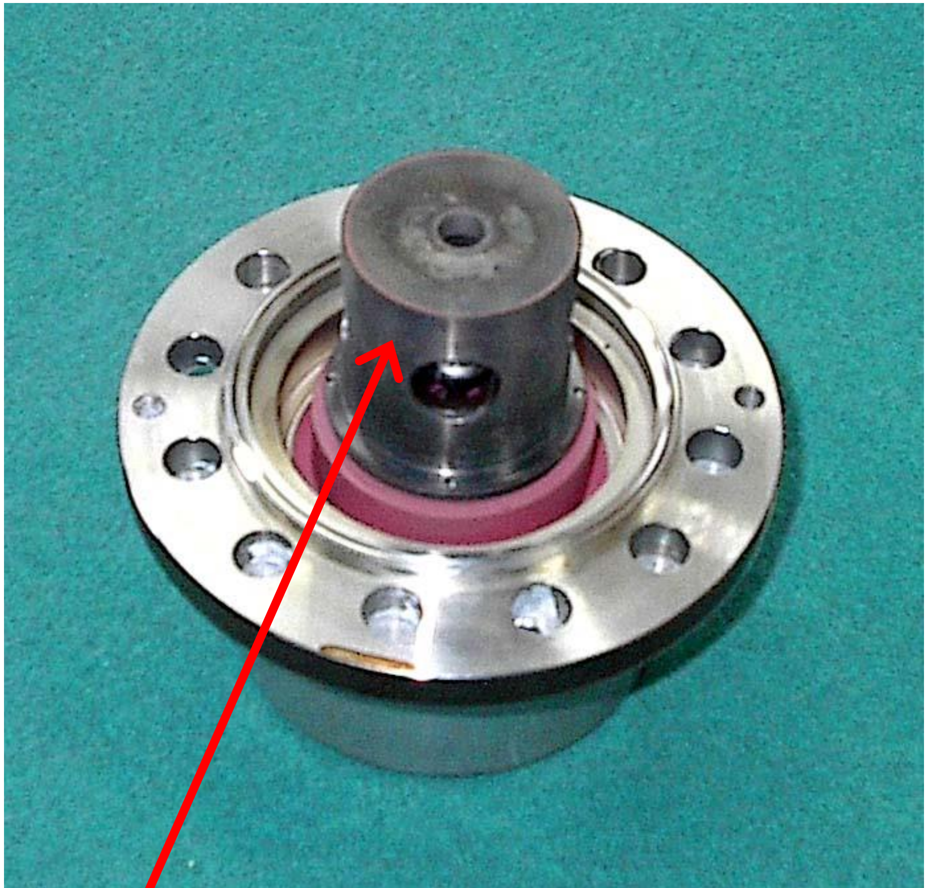
Point source – Pierce gun



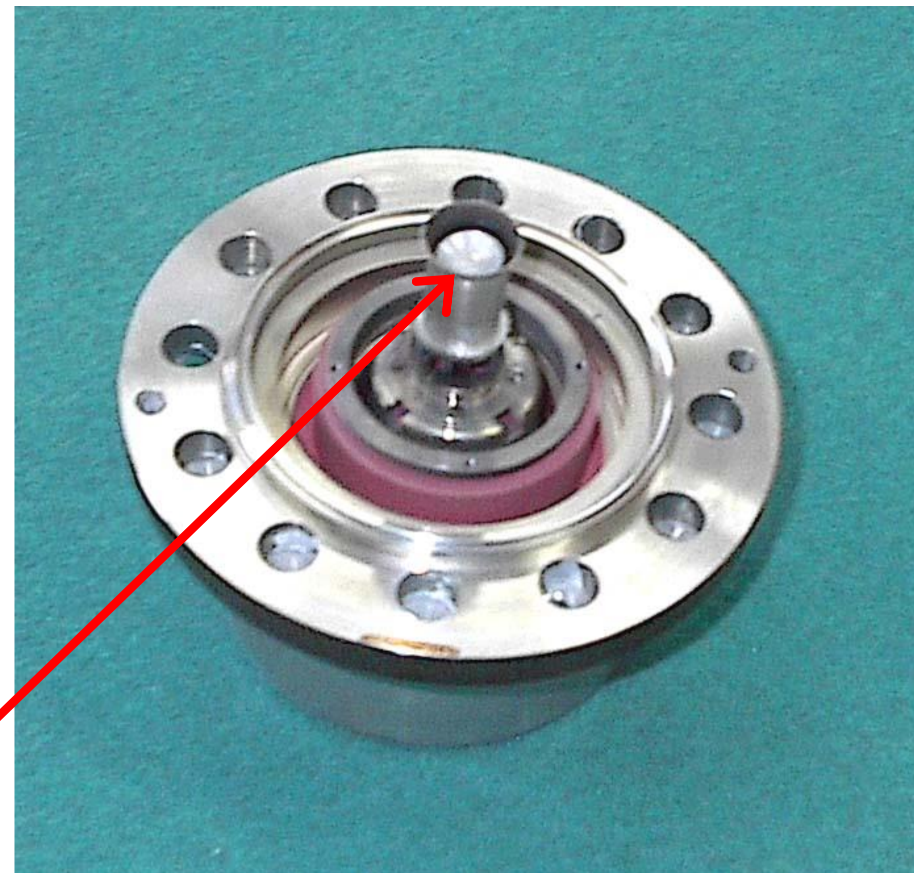
Electron gun triode type



Electron gun



Grid



Cathode

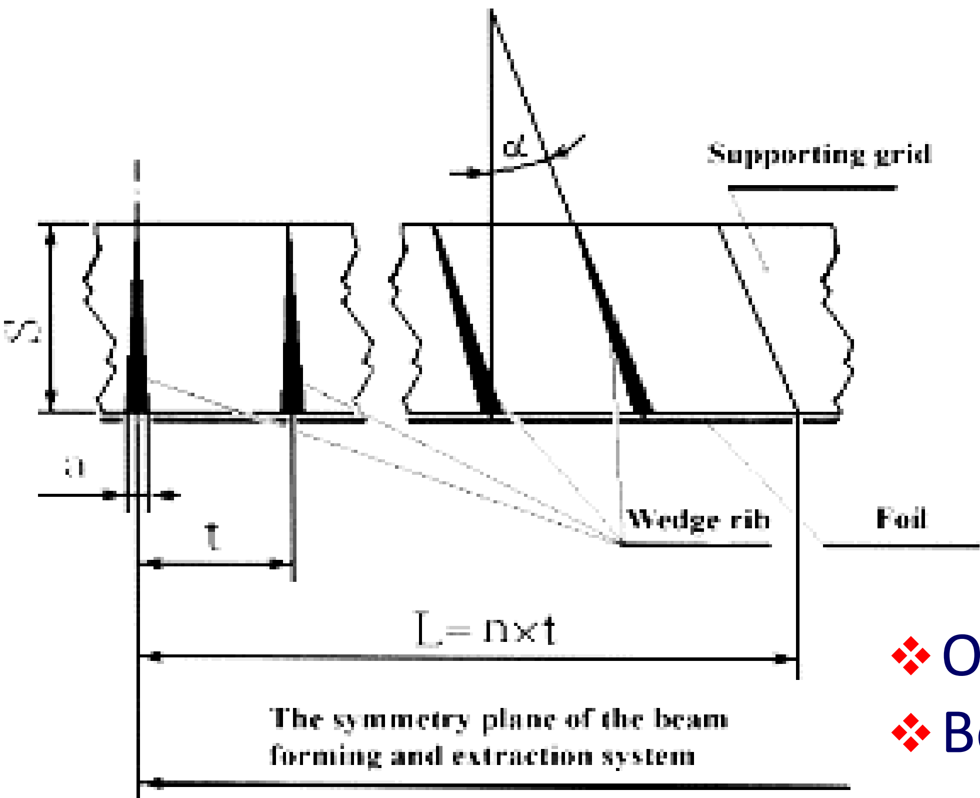
EXIT WINDOWS

- Electron beam extraction into the open air is usually performed through the thin metal foil to minimize the beam power losses.
- The low Z number materials are used like titanium, aluminum or their alloys and composites to reduce the energy loss.
- The energy deposited in window material increases window temperature what may require additional cooling system to avoid window breakdown.

Properties of various window materials

Material	beam current density [mA/cm^2]	max. temperature [^{o}C]	thickness [μm]
Al - alloy	0,1	200	40-60
Ti	0,15	250-300	10-50
Be	0,2	400	100
Ti - alloy	0,55	400-500	20-30
Ti - Al	0,7	900-1000	20-40

Extraction window with the supporting grid

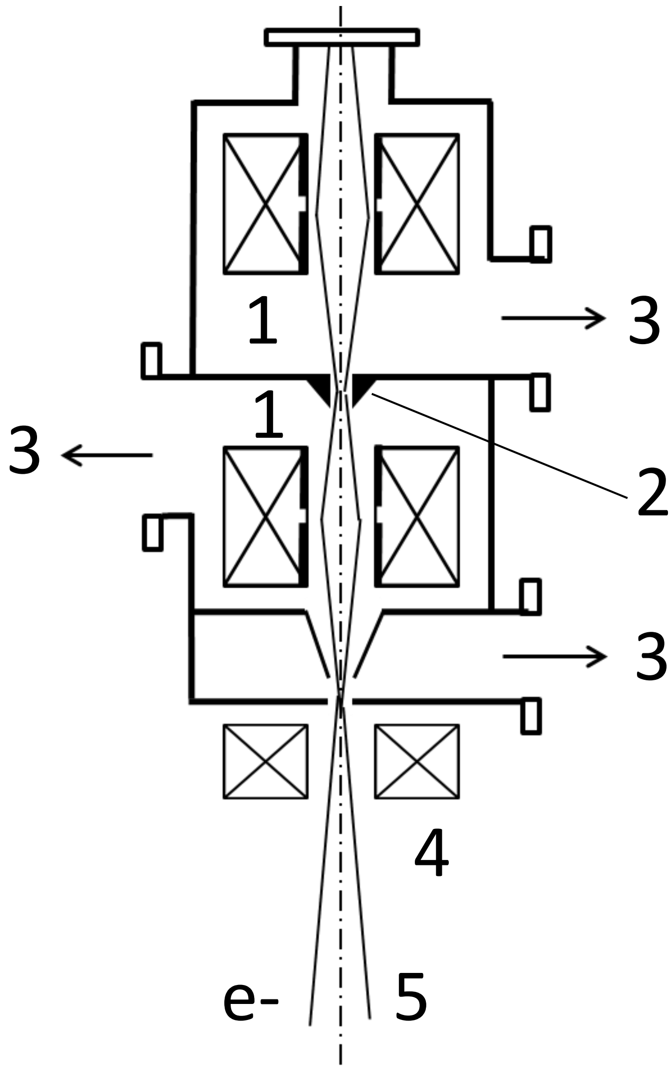


Experimental conditions:
- Energy 700 keV
- Beam current 1 mA
- Titanium foil 50 µm
- Beam spot 15x1200 mm
- Window beam current monitor distance 50 mm

- Optical transparency 0,86
- Beam current without supporting grid 0,9 mA
- Beam current with supporting grid 0,84 mA
- Beam current transparency 0,93

V.P. Ovchinnikov et al., RUPAC 2012

Schematic diagram of windowless extraction device



Beam power 100 kW,

Electron energy 1.5 MeV.

1 - magnetic lens;

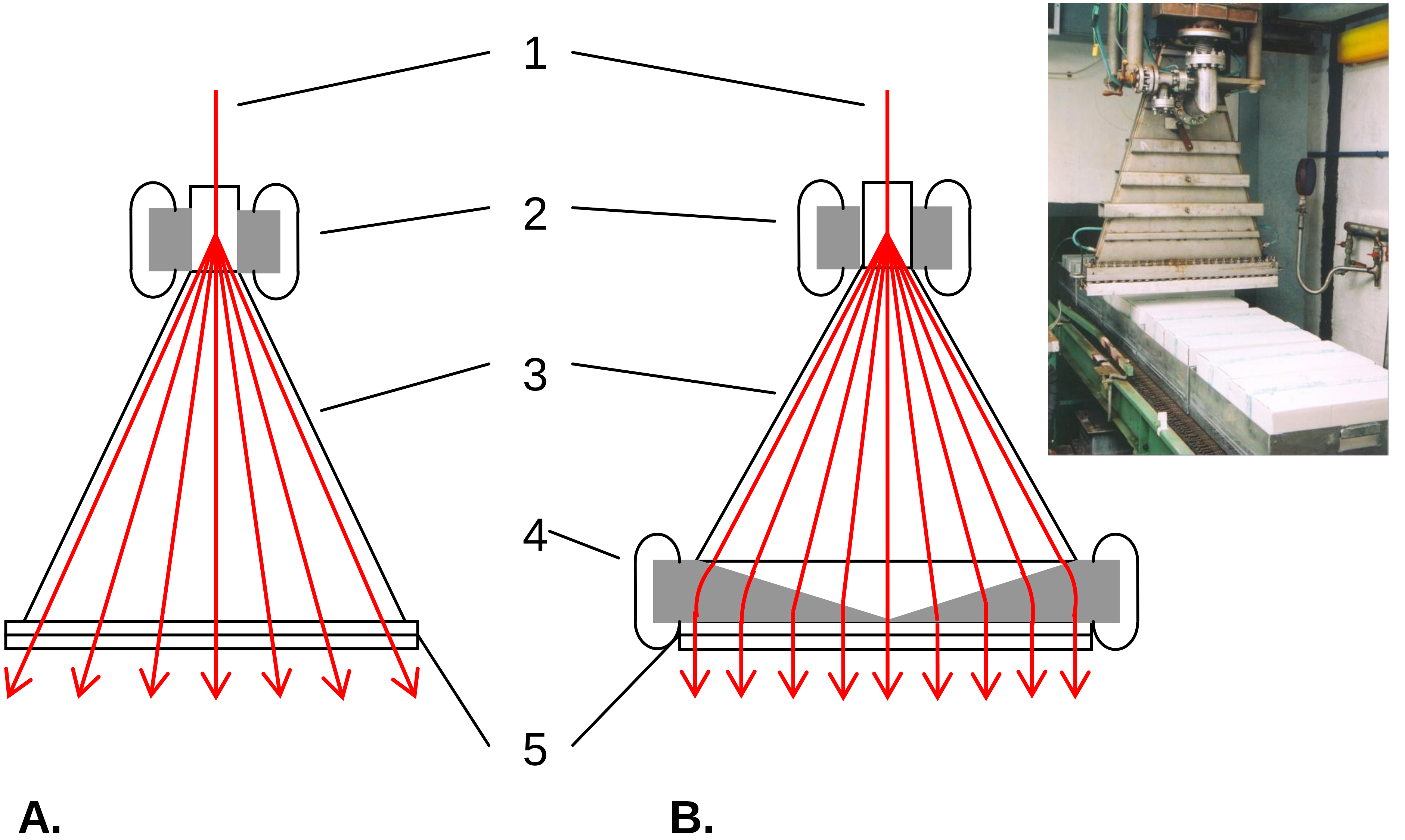
2 - diaphragms;

3 - vacuum lines;

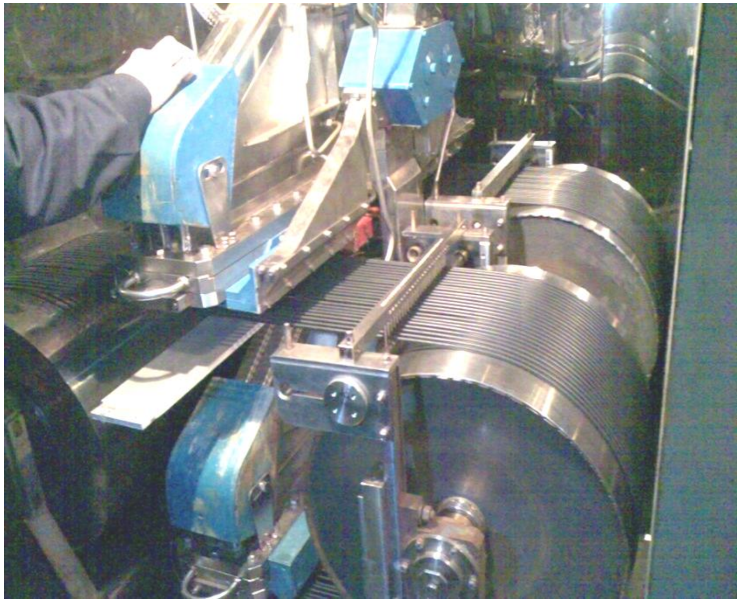
4 - scanning magnets;

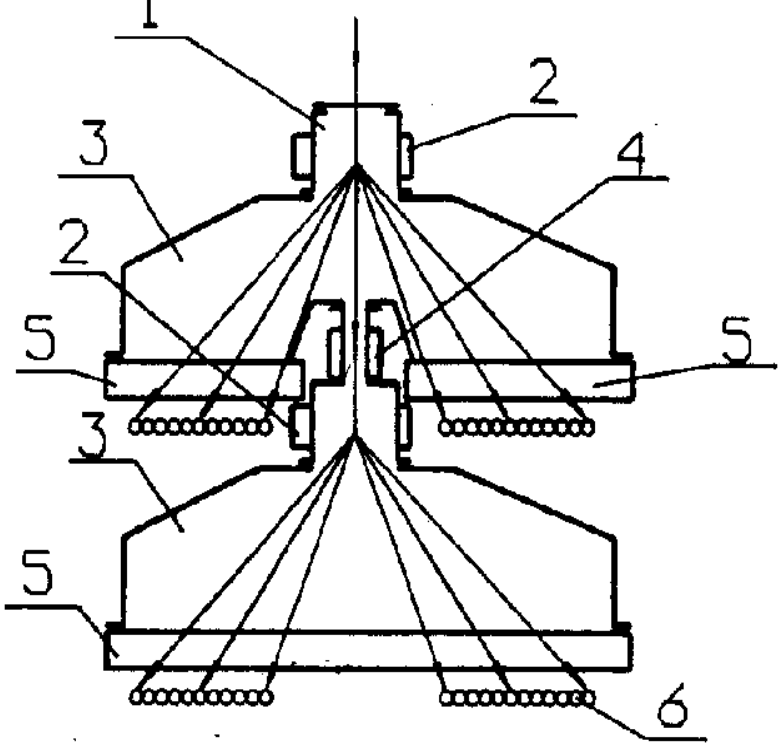
5 - beam envelope

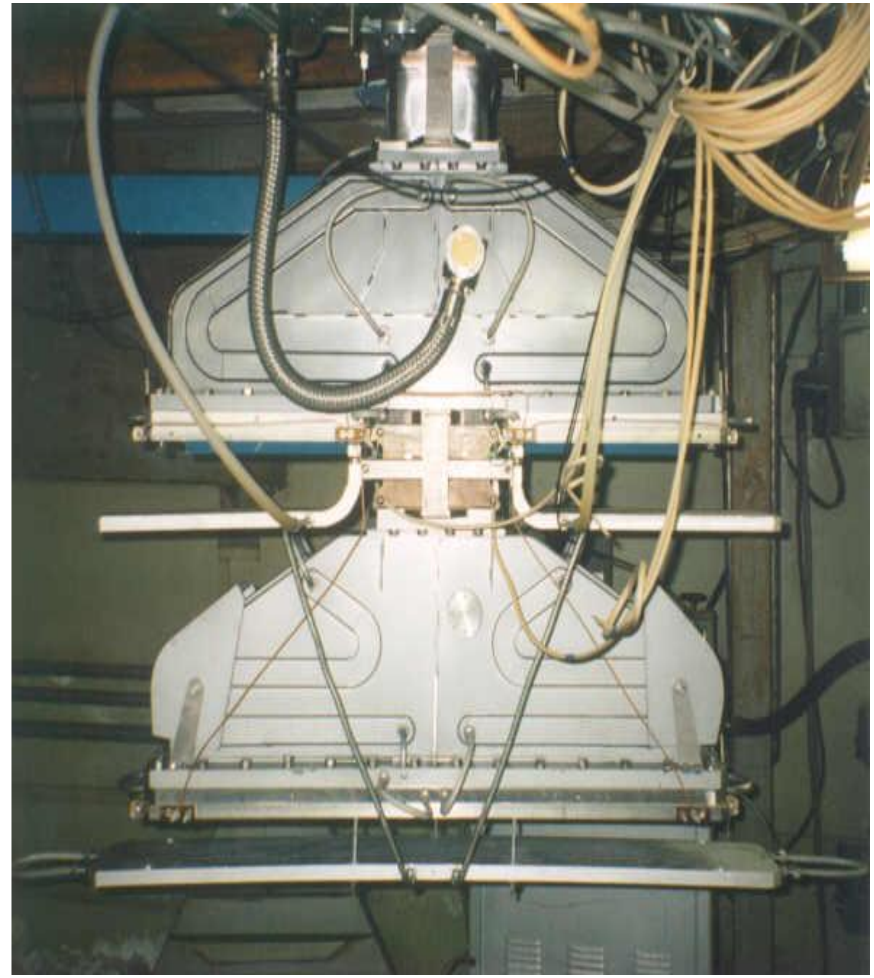
OUTPUT AND BEAM SCANNING DEVICES



Different configuration of accelerator output device (A – triangular scanning, B – parallel beam): 1 – electron beam; 2 – scanning magnet, 3 – scanner; 4 – correction electromagnet; 5 – output foil



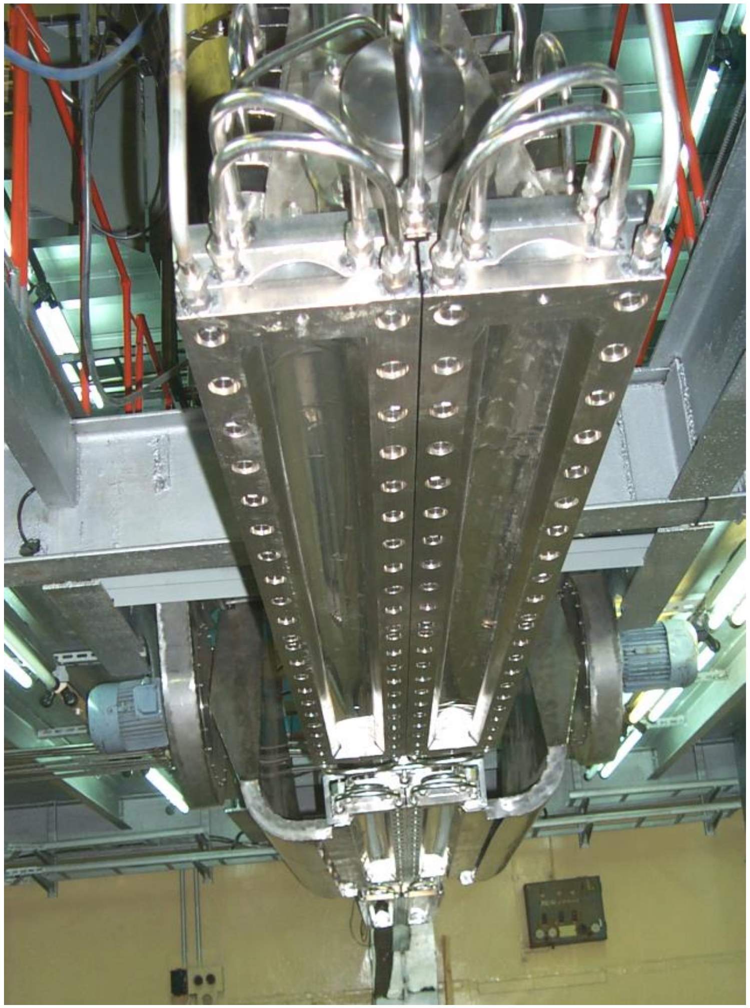


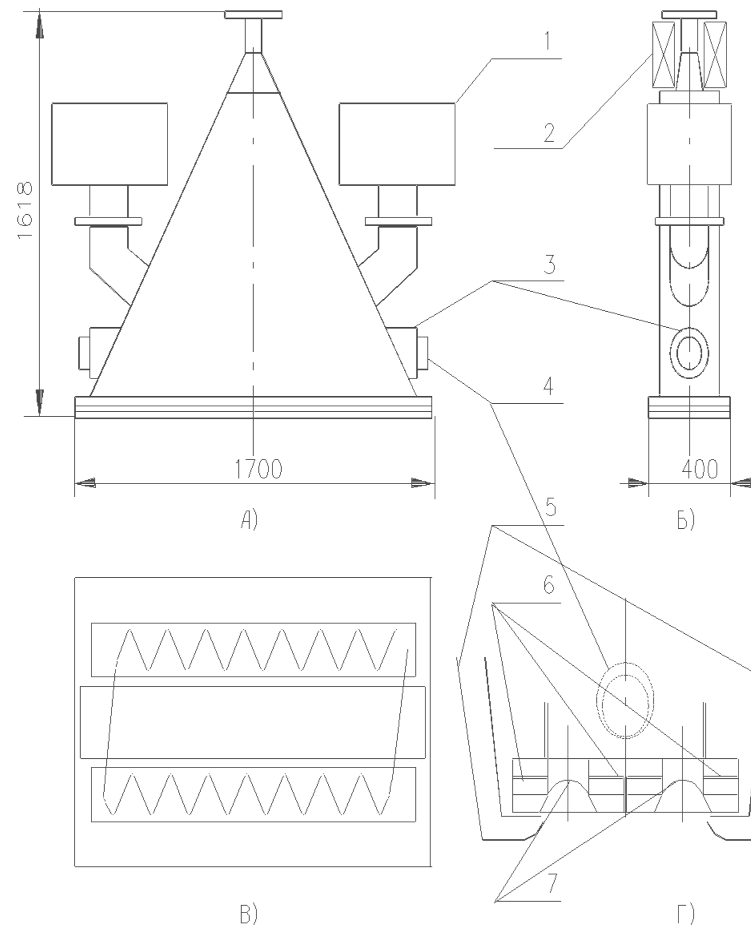


Beam scanning ILU 6

1, 3 – Vacuum system; 2 – Scanning and switching magnet; 4 – Focusing coil; 5 – Exit window; 6 – Irradiated cables or wires

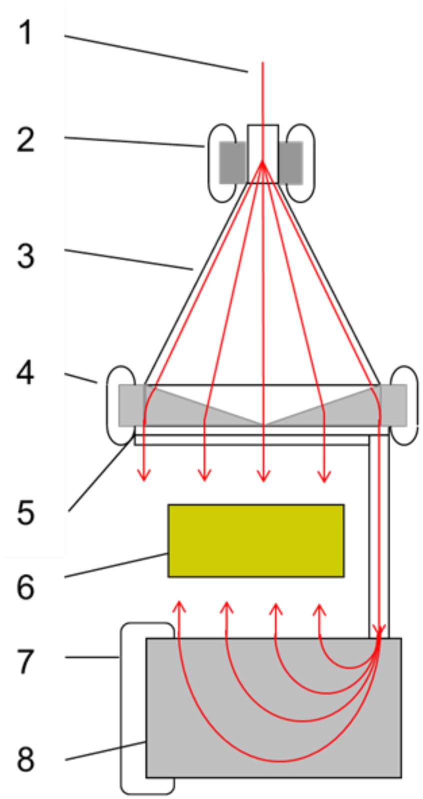
Double beam path scanning horn

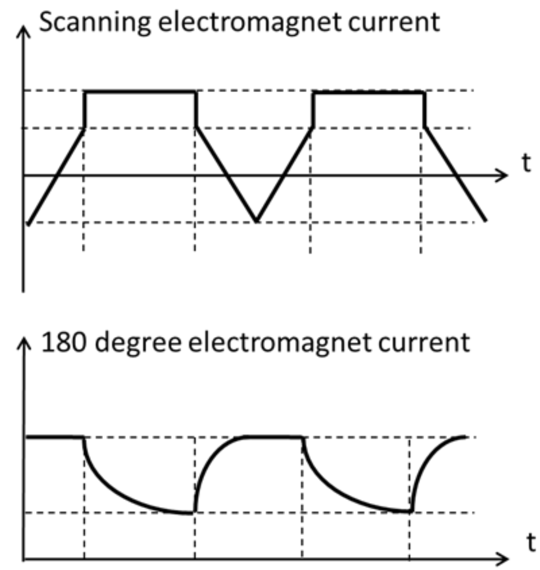




1 - Ion pumps, 2 - Coils and cores of the beam scanning system, 3 - Protection cylinder flange, 4 - Protection cylinder, foil blow, 5 - Air jet cooling, 6 - Frame for fixation of foil, 7 - extraction foils.

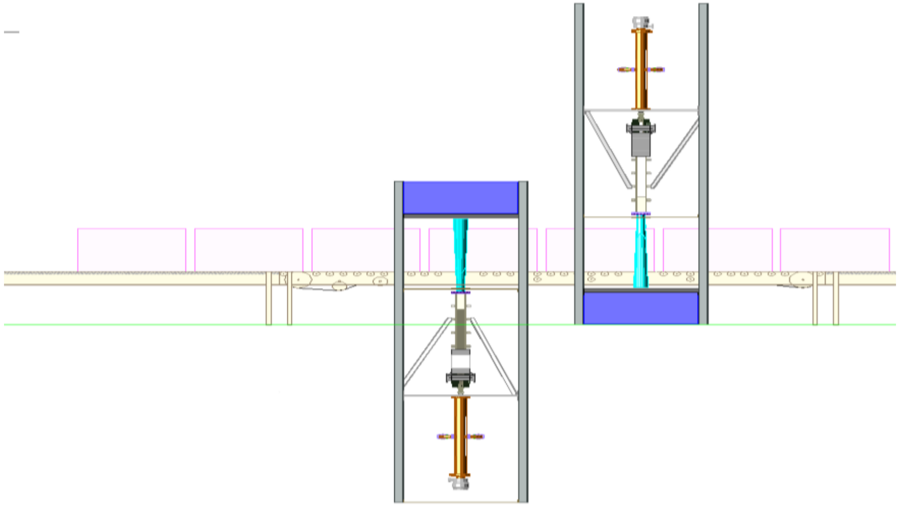
Output device for two sided irradiation





1 – Electron beam; 2 – Scanning electromagnet, 3 – Scanner; 4 – Correction electromagnet; 5 – Output foil; 6 – Irradiated box; 7 – Electromagnet; 8 – Vacuum chamber

Two + double

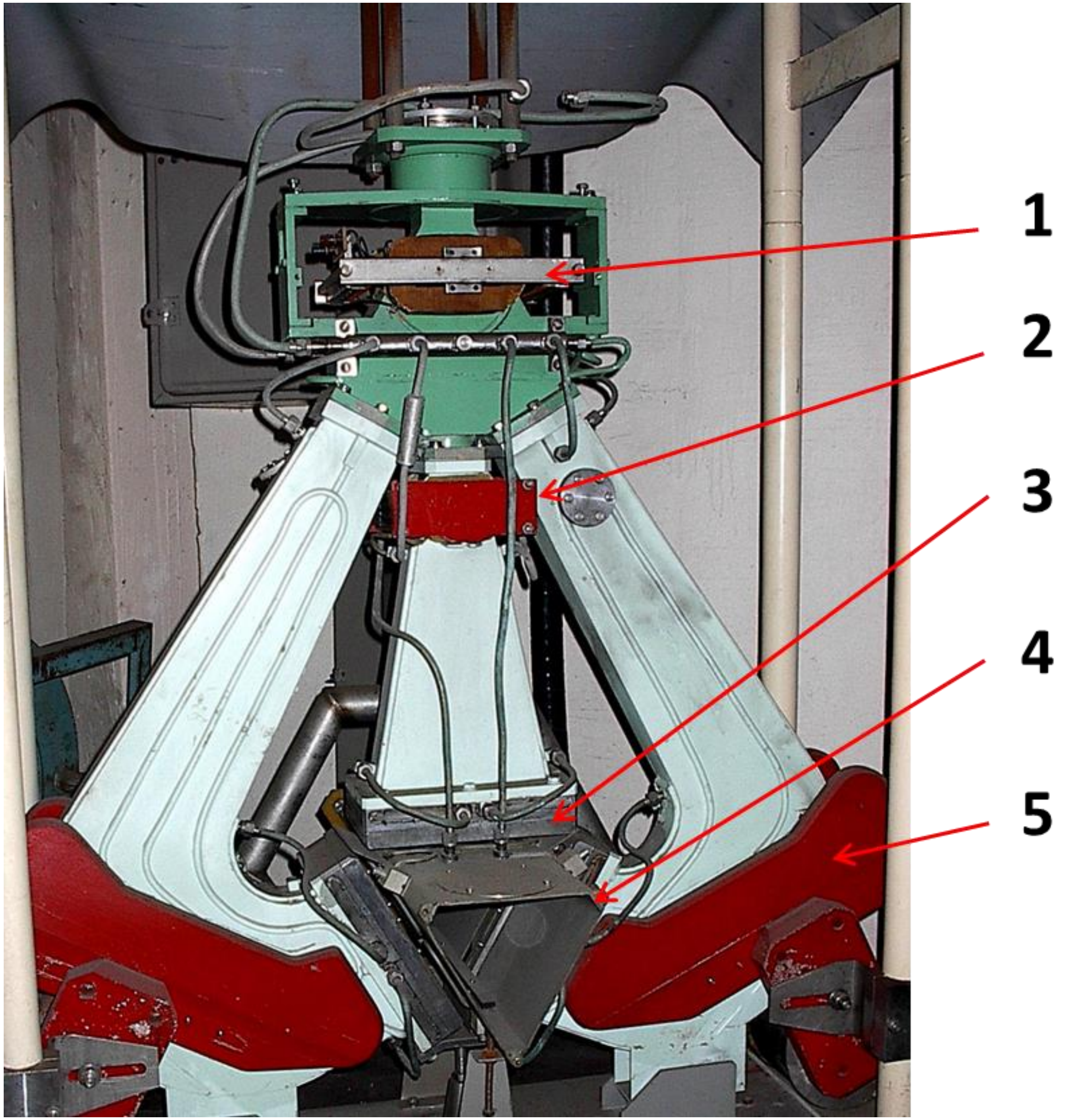


Double side irradiation auxiliary equipment

STUDER HARD

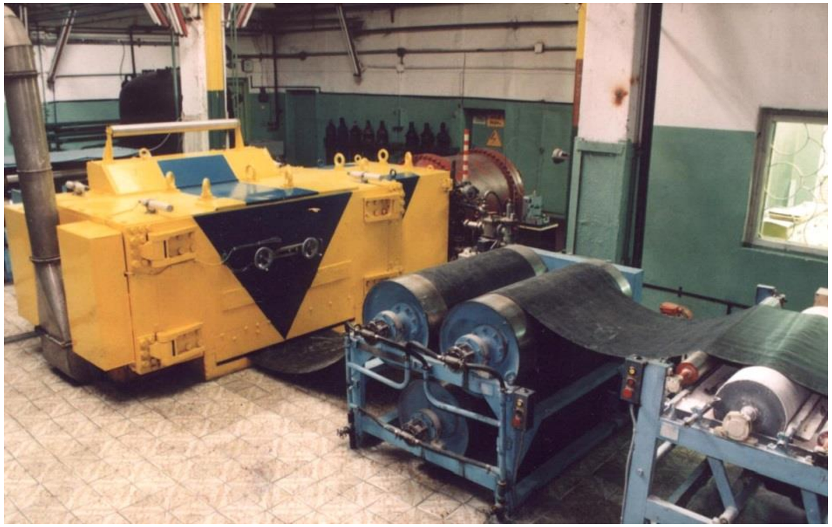
Three sides irradiation of cylindrical objects

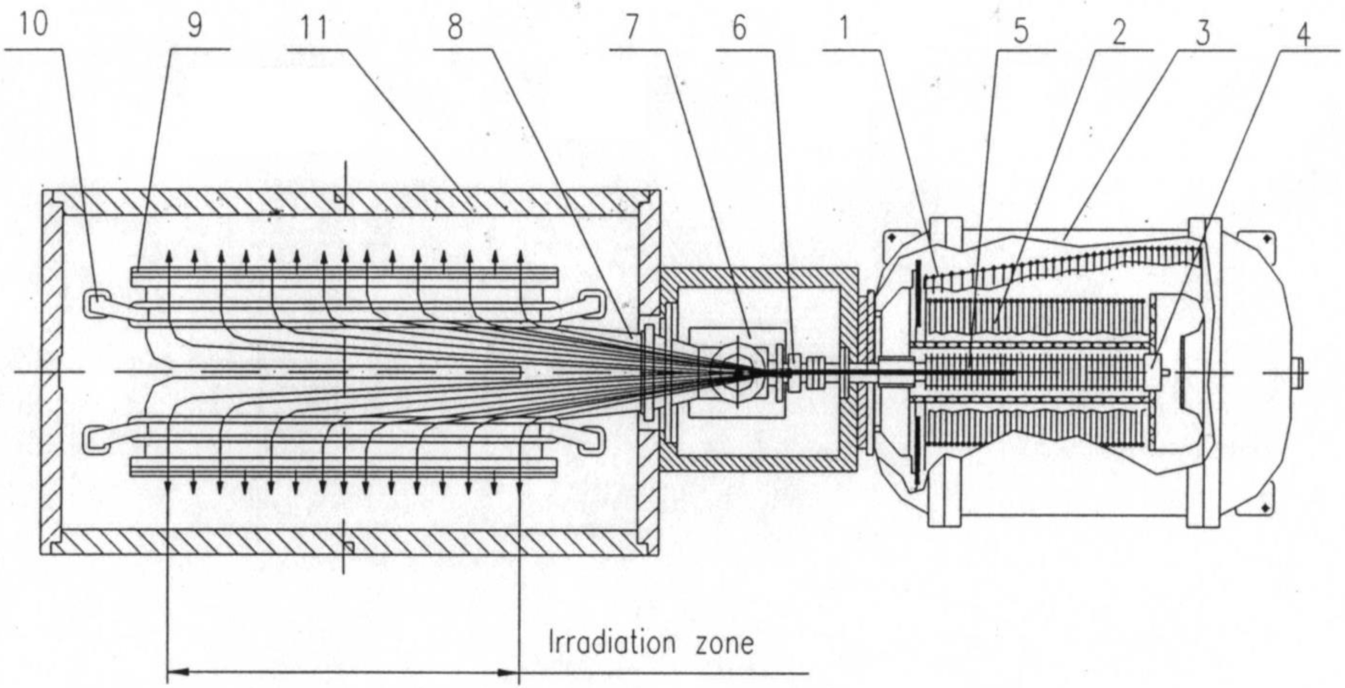
1 – Switching magnet;
2, 5 – Scanning magnets;
3 – Output window;
4 – Irradiation zone.



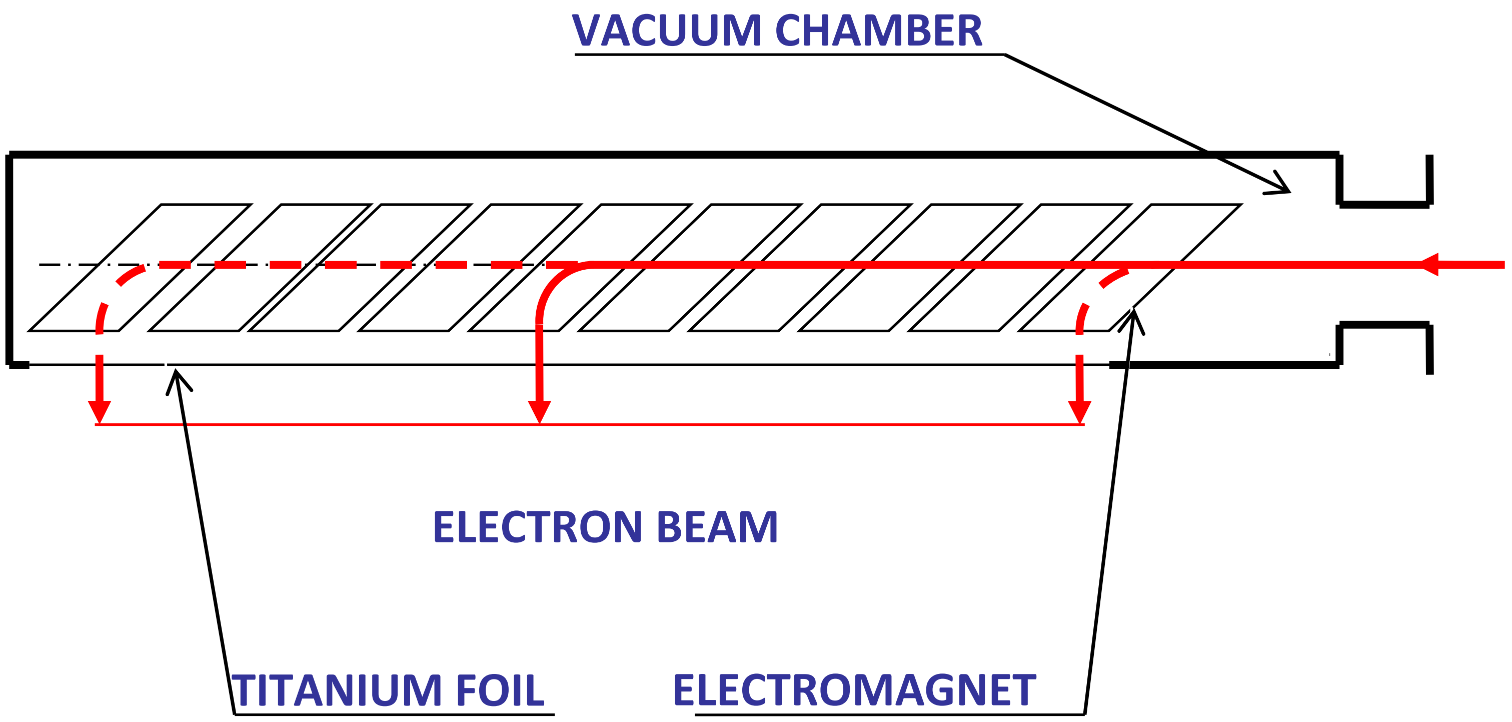
ELECTRON-10 (0.5-0.75 MeV; 50 kW)

1 – Primary winding; 2 – Secondary winding; 3 – Pressure vessel; 4 – Electron source; 5 – Accelerating tube; 6 – Scanning device; 7 – Vacuum pump; 8 – Vacuum chamber; 9 – Outlet window; 10 – Turning magnet; 11 – Radiation shielding.



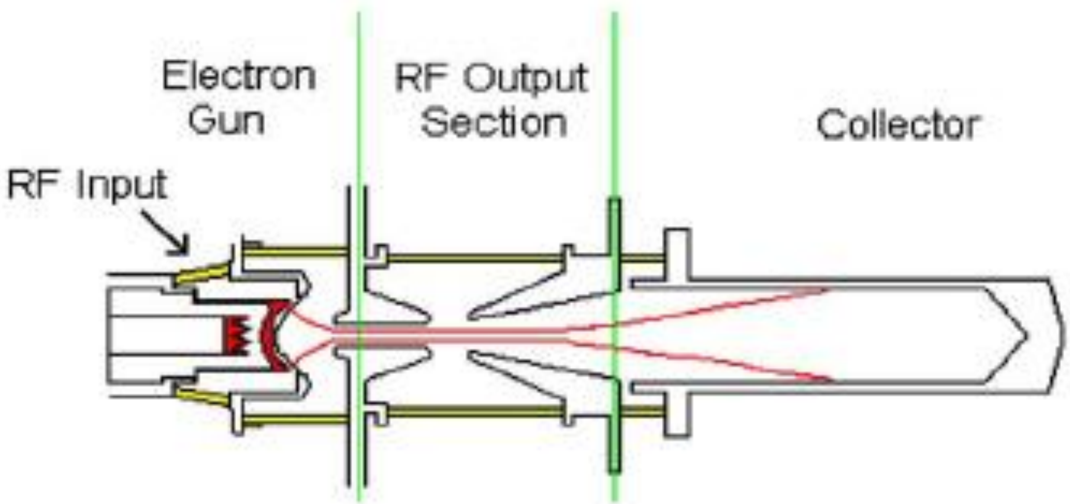


LINEAR SCANNING SYSTEM



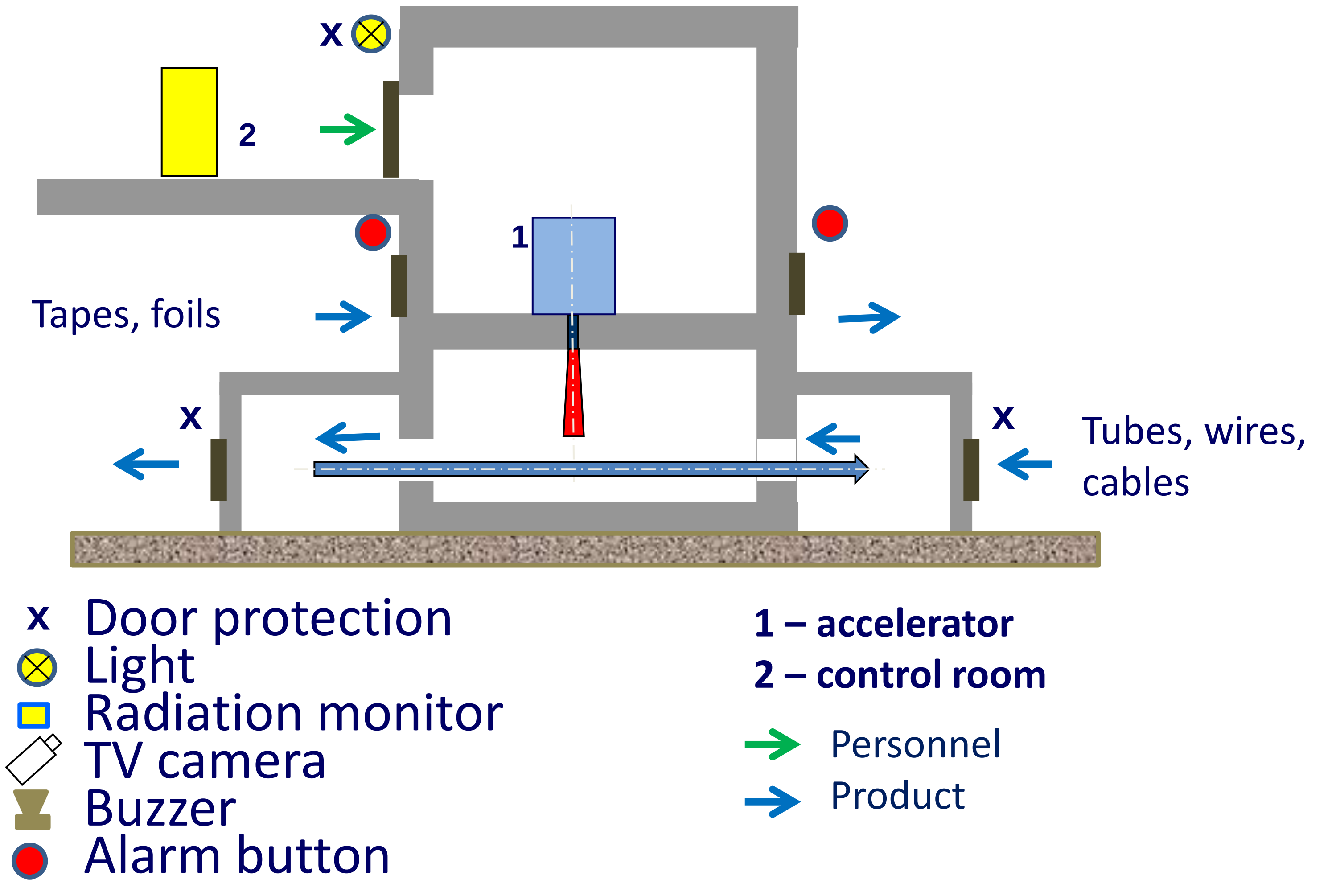
RF (radio frequency) sources

Type of generator	RF power	Efficiency
Semi-conductor	5 kW	40 %
Tetrode	> 60 kW	75 %
IOT	90 kW	75 %
Klystron	> 1MW	70 %

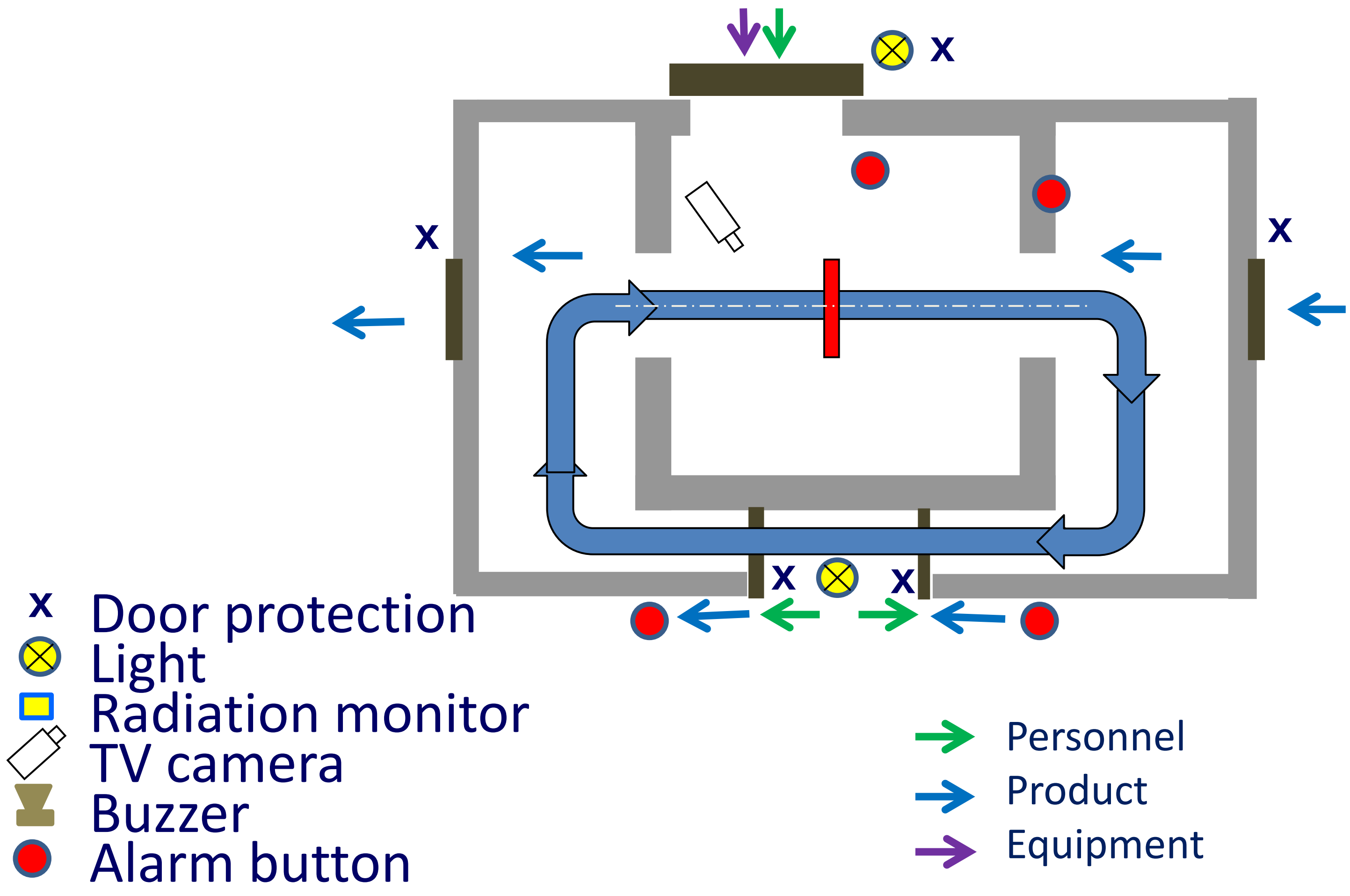


IOT tube
(cw microwave
source)

Accelerator IłU 6 (pilot plant)



Accelerator IŁU 6 (pilot plant)

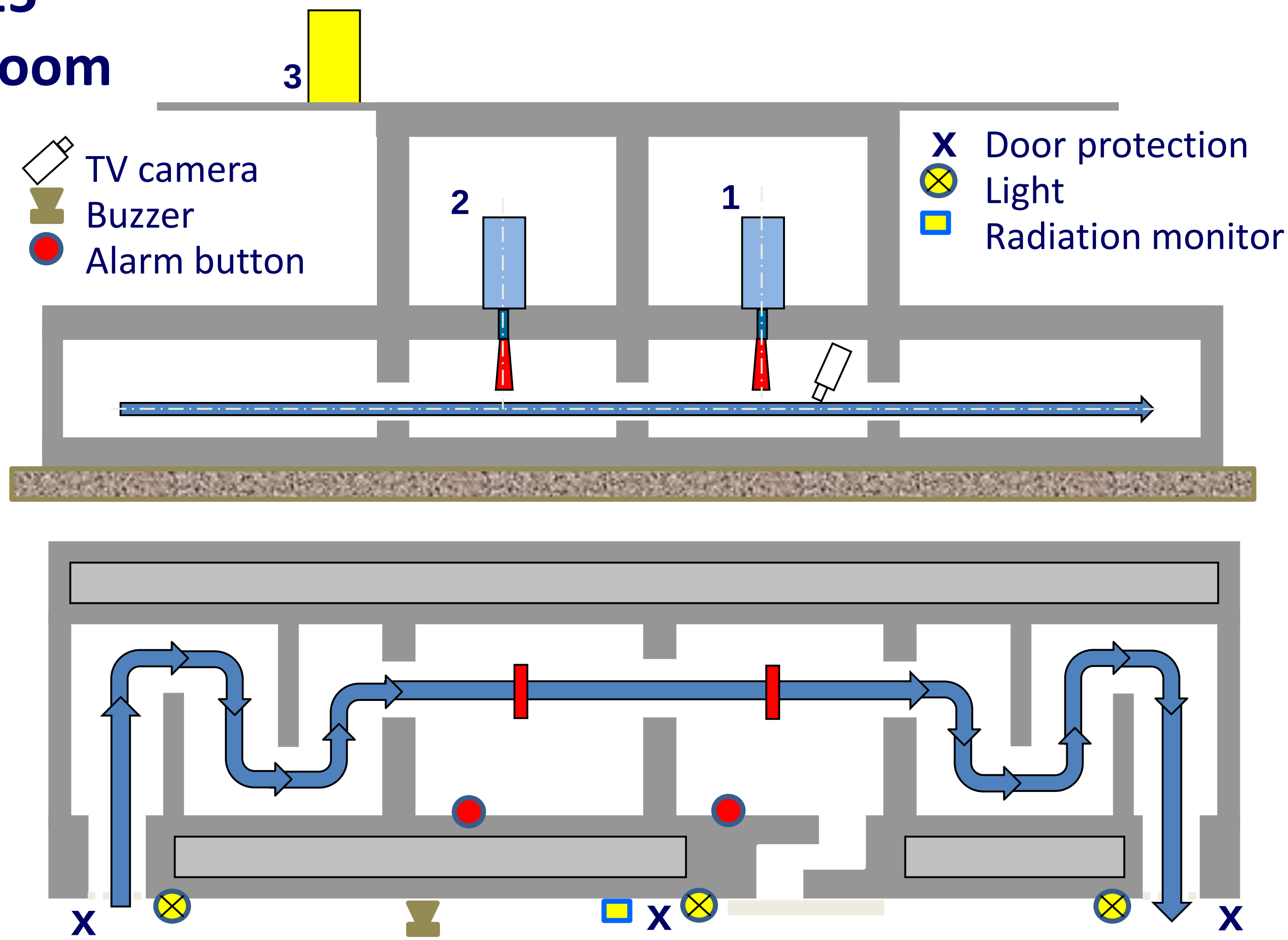


Radiation sterilization facility

1 – Elektronika 10/10

2 – LAE 10/15

3 – control room



Radiation sterilization facility Elektronika 10/15

(A. Barejka, USA)

Market Prospects – Positive Developments

- Low-energy EB continues to grow at a fast pace with the downsizing of equipment making EB more affordable.
- Mid-energy EB remains the mainstay of the entire industry but in historic markets.
- Very high-power EB accelerators have made X-ray processing practical.

(B. Han, Korea)

Barriers for industrial applications

- Public acceptances (radiation safety, new events).
- Technical problems (reliability for one year-round operation).
- Regulation from authorities.
- Competition with other processes (economics - high investment cost, long returns).

(S. Machi, Japan)

Trends in application of accelerators in Japan

- Increasing high energy accelerators for sterilization.
- Increasing low energy accelerators for curing of coatings and printing.
- Increasing low energy accelerators for treating PET bottles and food packages.
- Increasing export of accelerators for Asian countries (~10 per year).

3.2. Gamma facilities

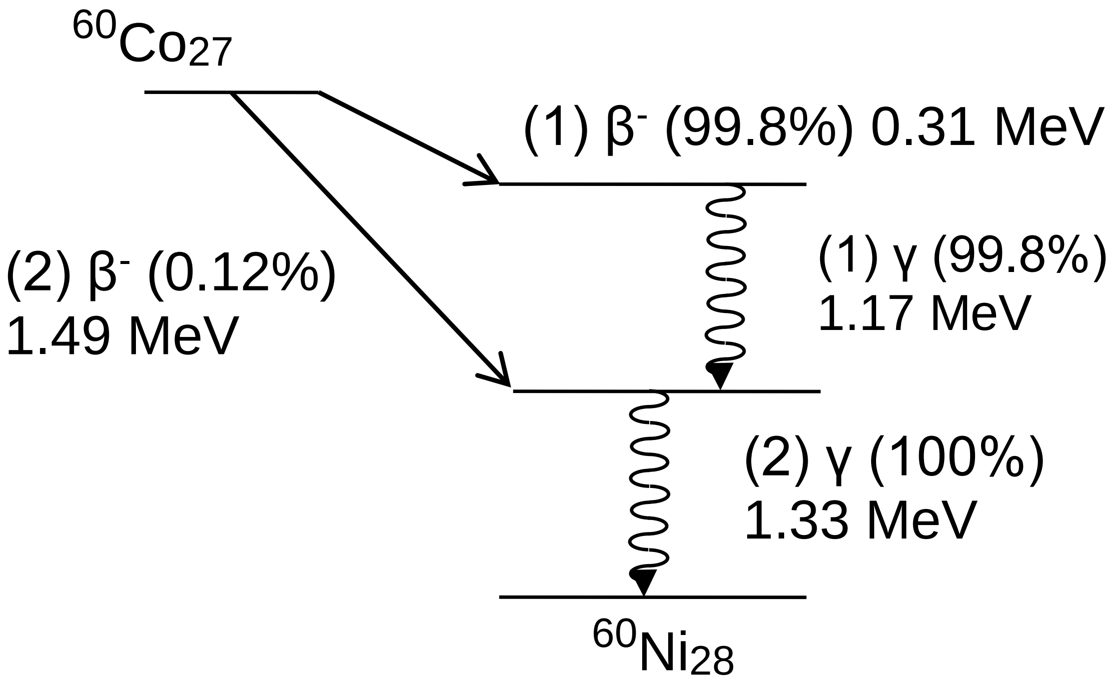
Decay Data of Cobalt-60

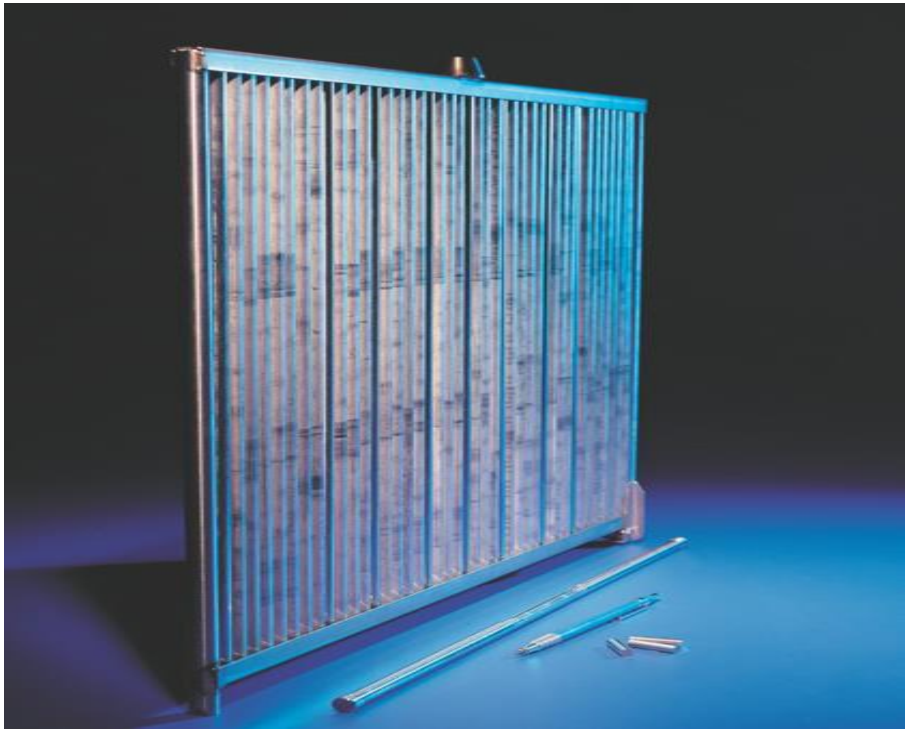
$^{59}Co_{27} + n \rightarrow ^{60}Co_{27}$

$1\ Ci = 3.7 \times 10^{10}\ Bq = 37\ GBq$

Half life – 5,2 years

1 day	0,9996
1 week	0,9975
1 month	0,9889
1 year	0,8769
10 years	0,2685
15 years	0,1391
30 years	0,0194

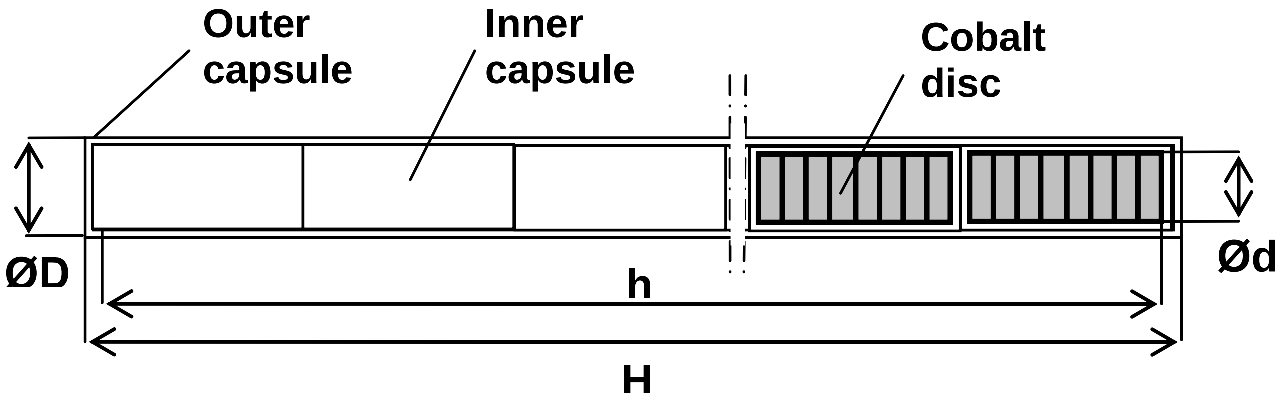




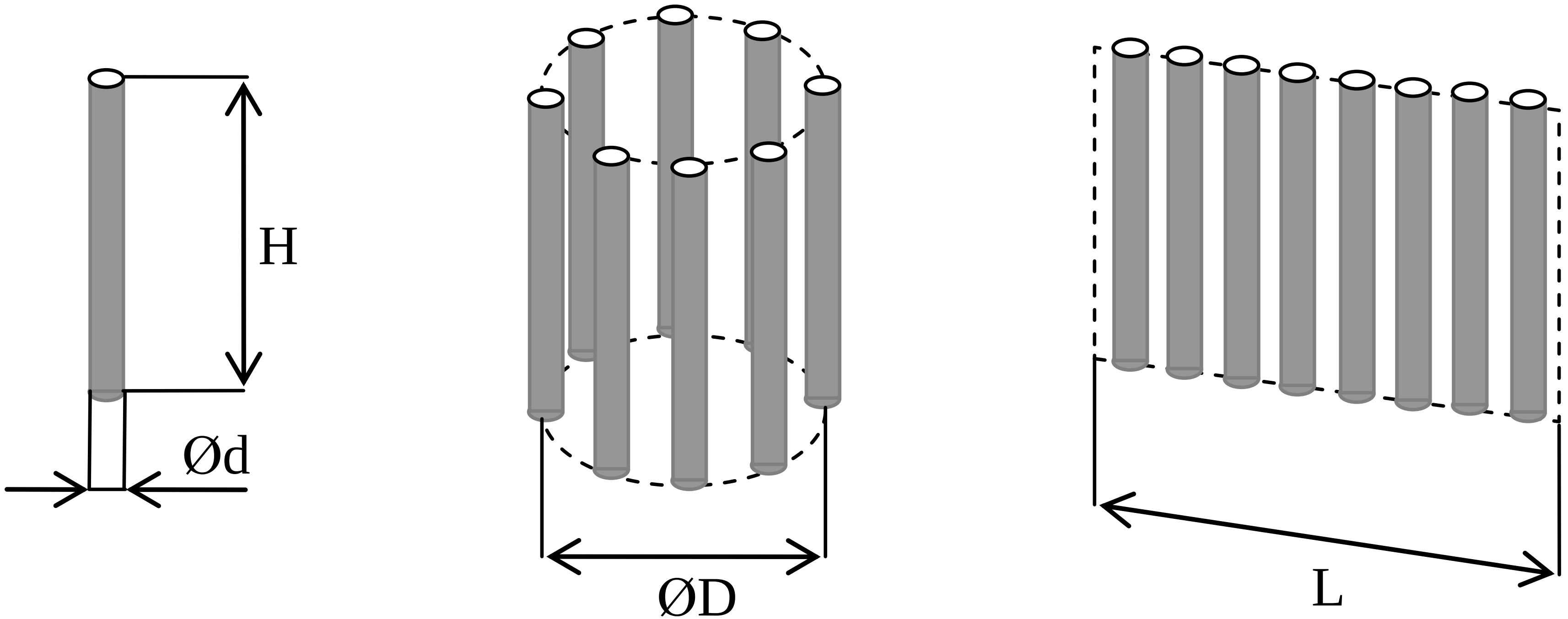
Cobalt-60 sources

C-188 double-encapsulated cobalt-60 source provided by MDS Nordion:

- Standard source activity up to 14 250 Ci,
- Dimensions 11.1 mm in diameter, 451.6 mm in length,
- Weight 0.24 kg,
- Warranty 20 years.



Typical configuration of cobalt sources



INCT laboratory Co^{60} sources

MINEYOLA 1000
Max. 0,9 kGy/h
Min. 0,08 kGy/h

GAMMA CHAMBER
5000; 7 kGy/h

ISSLEDOWATEL
<1 kGy/h

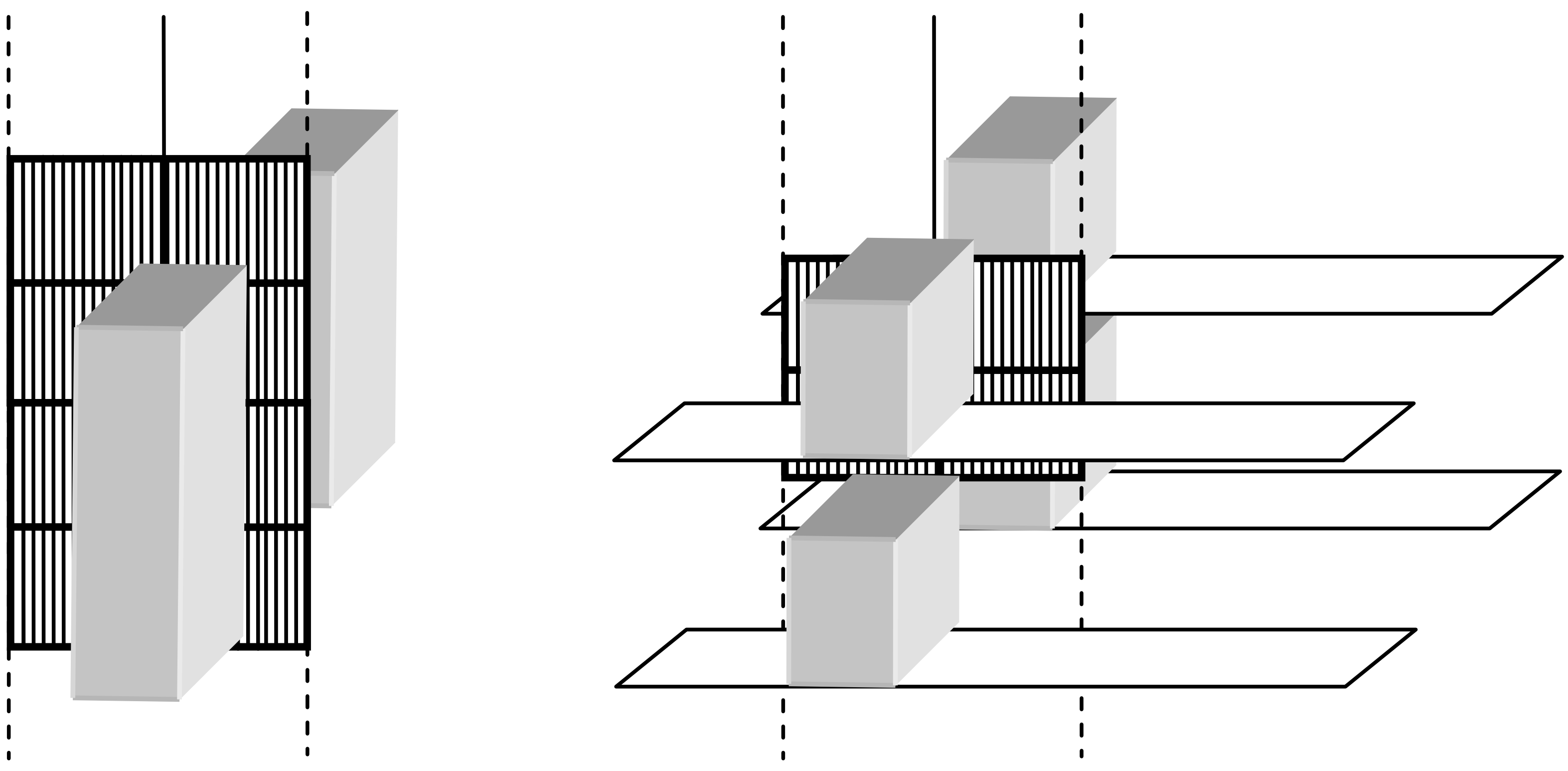
Geometry of irradiation process:

A – source overlap product,

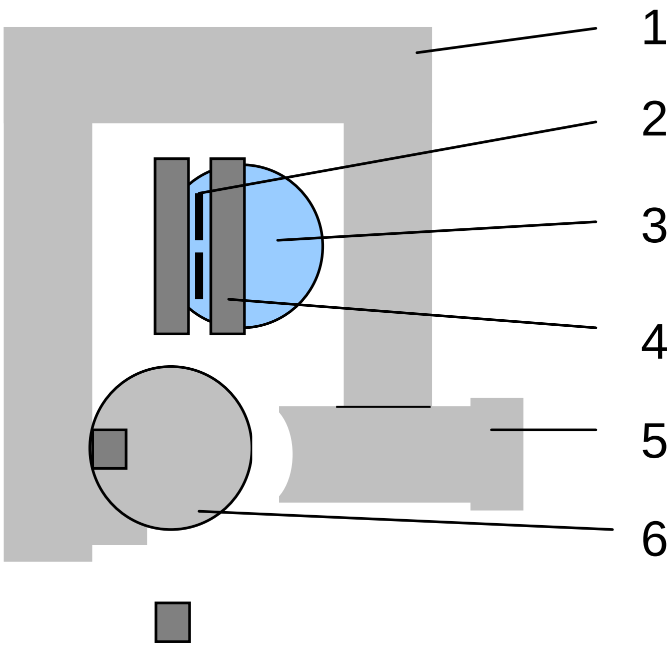
B – product overlap source.

A.

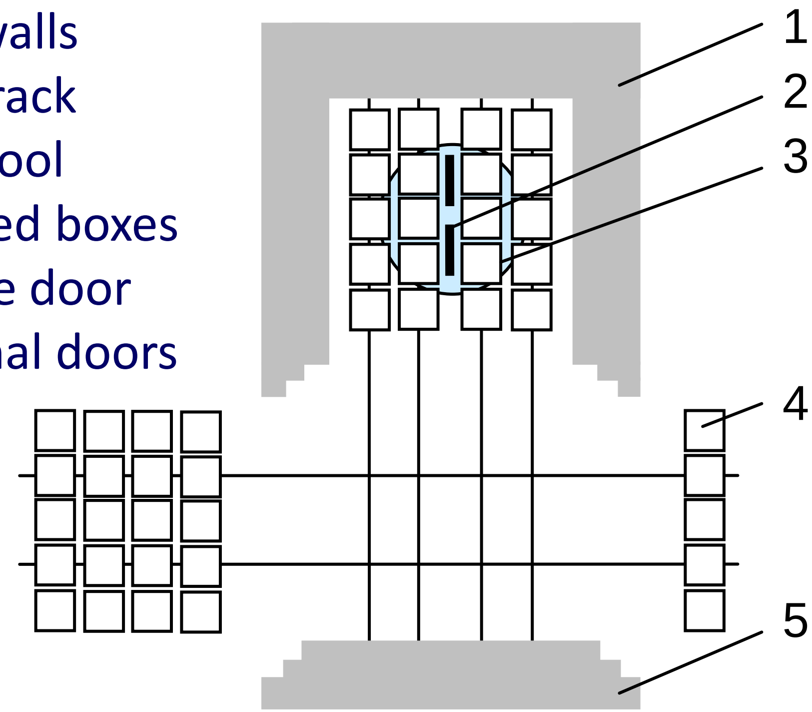
B.



Small-scale industrial gamma irradiators



1 – shield walls
2 – source rack
3 – water pool
4 – irradiated boxes
5 – movable door
6 – rotational doors

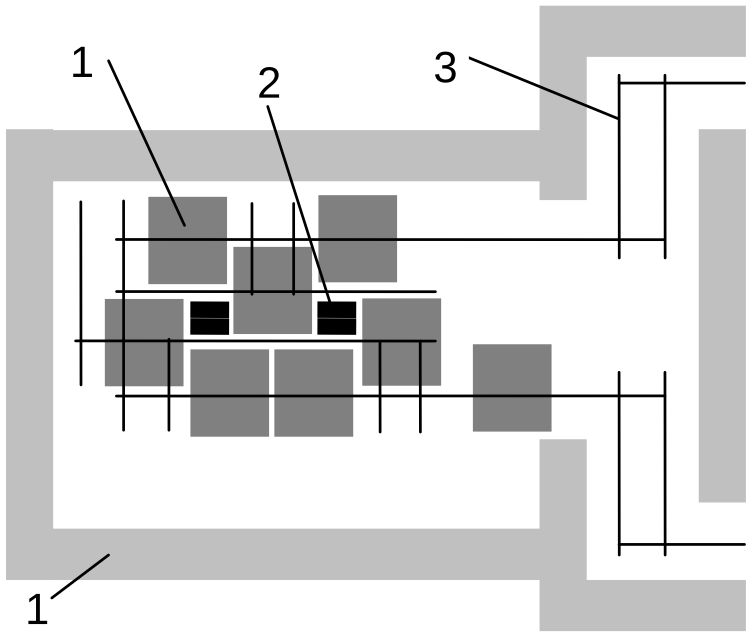


Radiation Technology Center, IPEN, Brazil

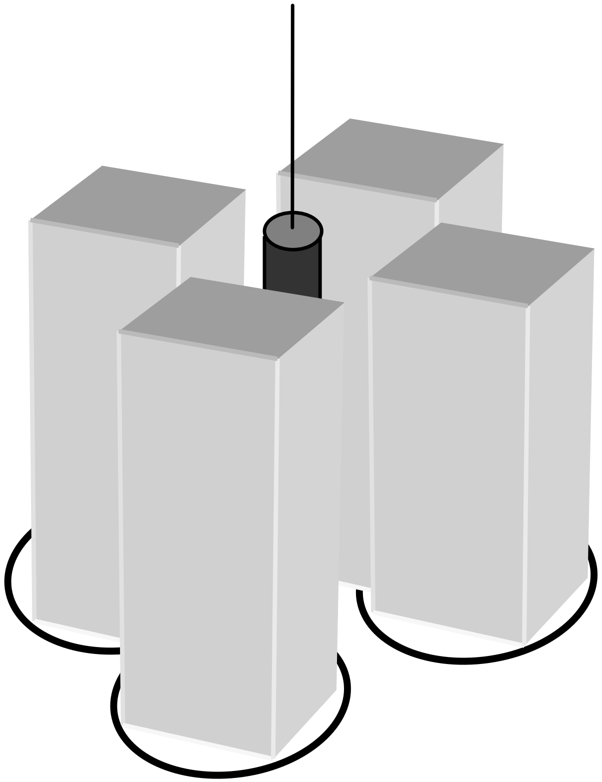
Floor space	76 m^2
Irradiator capacity	up to 1 MCi Co-60
Tote boxes up to	16 totes
Tote box volume	270 l
Max weight per tote	300 kg

BREVION provided by MDS Nordion

Floor space	30.5x18.3 m
Irradiator capacity	up to 1 MCi Co-60
Tote boxes	up to 40 totes per source pass
Tote box dimension	508x508x867 mm
Max weight per tote	88 kg
Product density	<0.1-0.4 g/cm^3
Batch interchange time	4-5 min



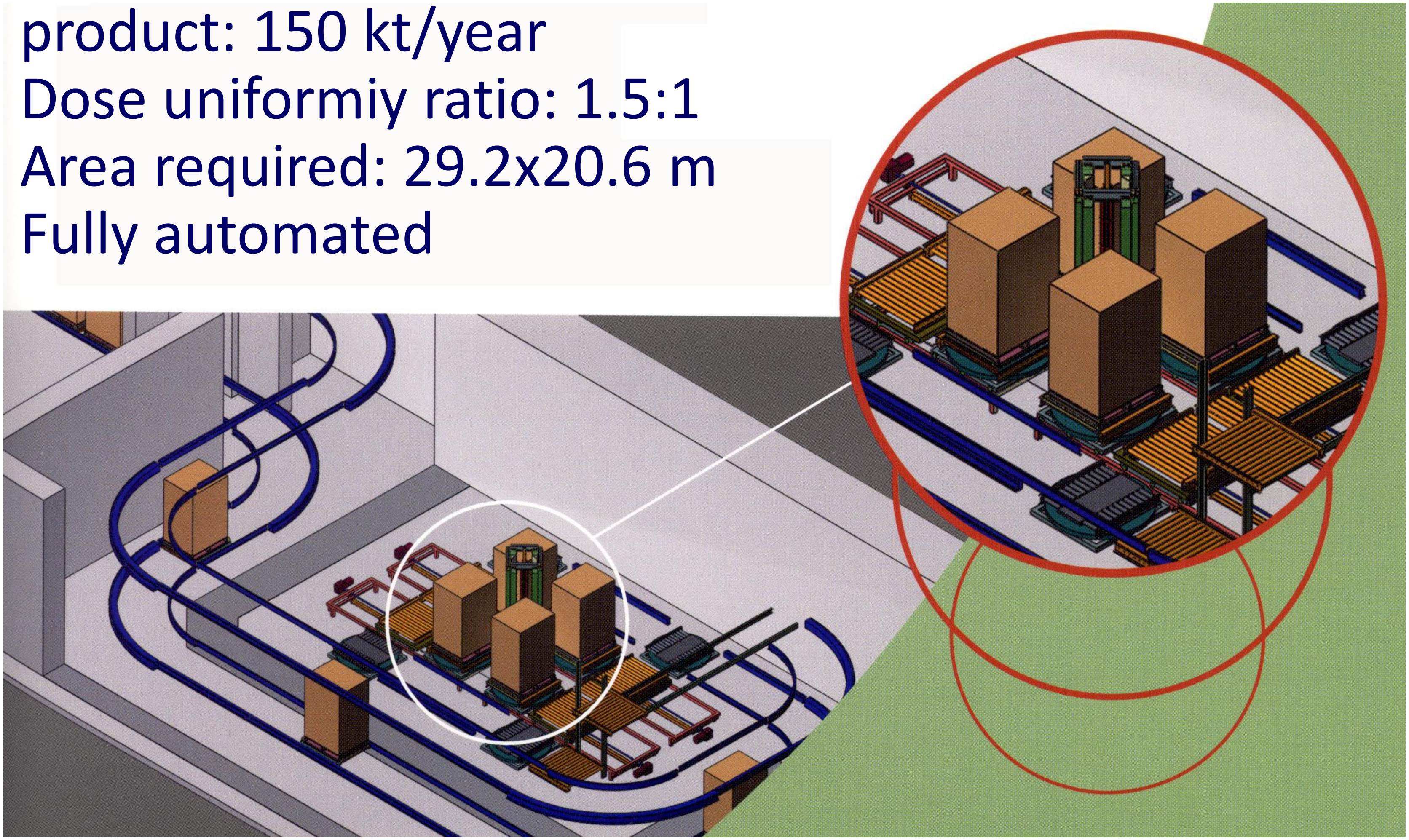
Top view of seven position pallet irradiator: 1 – pallet, 2 – source rack, 3 – maze transport, 4 – shielding wall



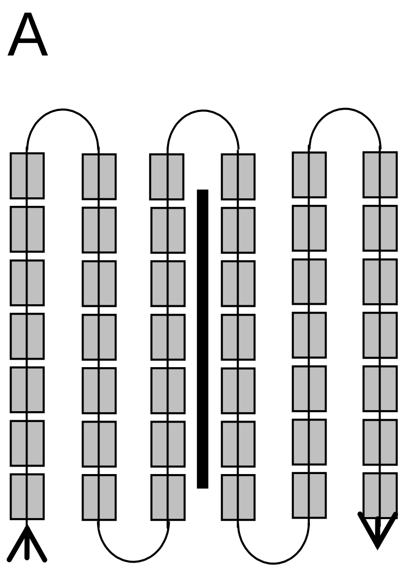
Product and source Configuration in „Micro-Cell” irradiator

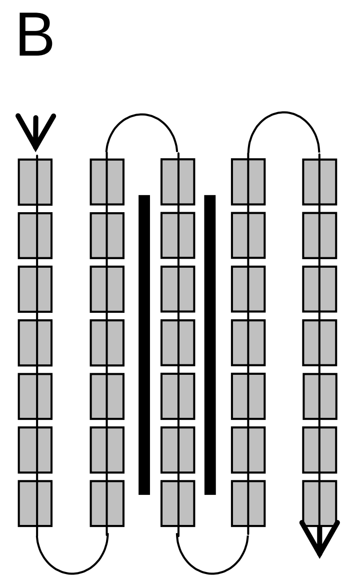
QuaduraTM

Gamma Pallet Irradiator
MDS Nordion
Processing capacity of food product: 150 kt/year
Dose uniformiy ratio: 1.5:1
Area required: 29.2x20.6 m
Fully automated



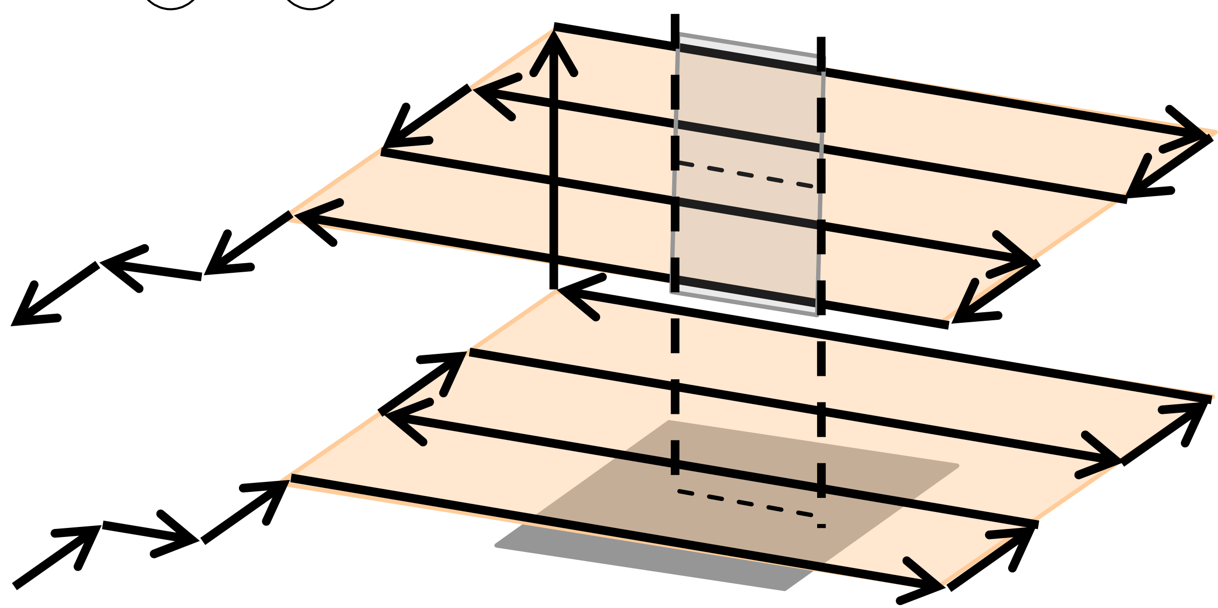
Conveyor systems





Sequences of product movement during irradiation process:
A – with one rack,
B – with two racks

Two levels and two rows located at each side of source rack



3. X-rays facilities

Medical applications

- X – Medical and dental diagnostics
- CT – Computer tomography
- X – Mammography

Industrial applications

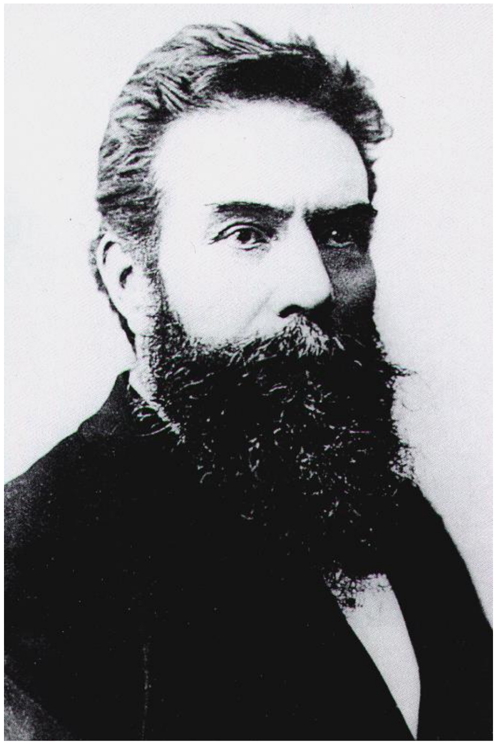
- NDT – Non destructive testing
- CT – Computer tomography
- Radiation processing

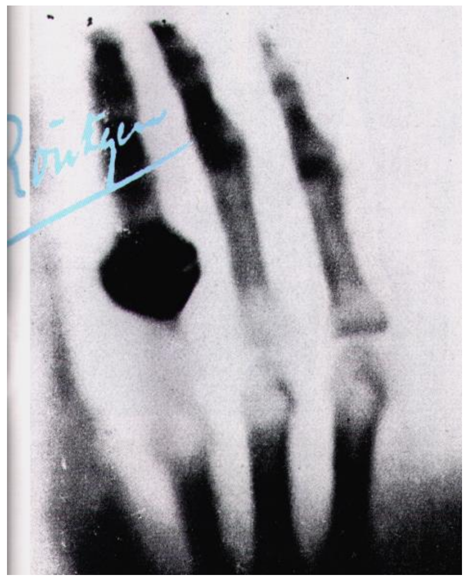
Custom inspection

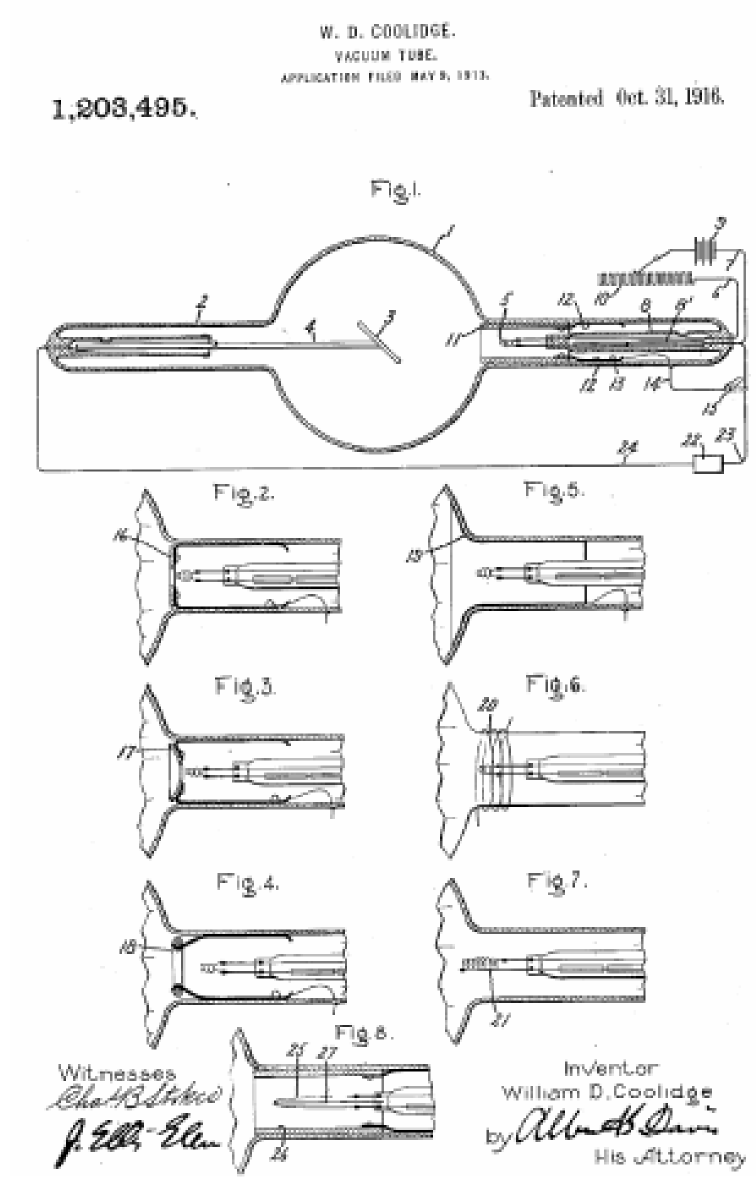
- Baggage
- Container
- Personal

Fields of x-rays application

Wilhelm Conrad Röntgen
(X-ray discovery 1895)



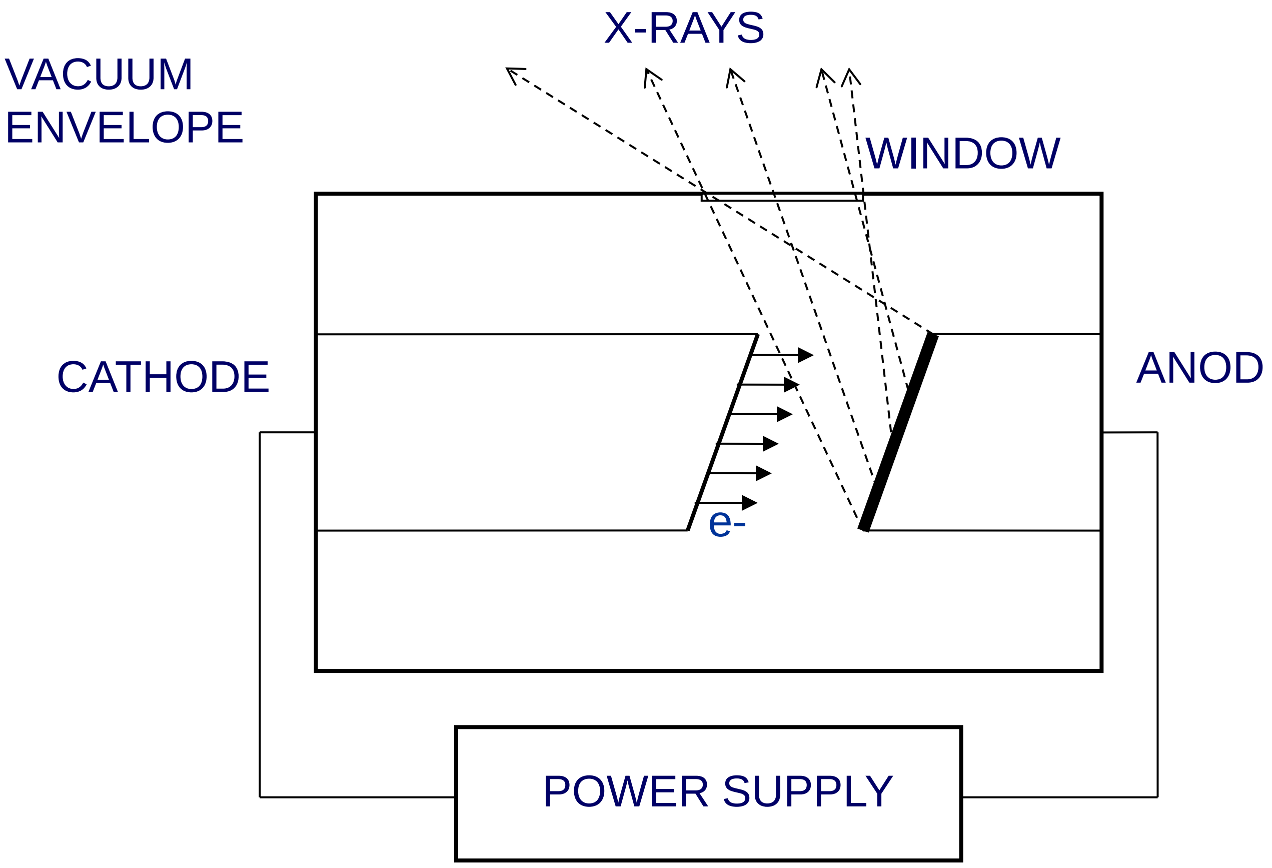




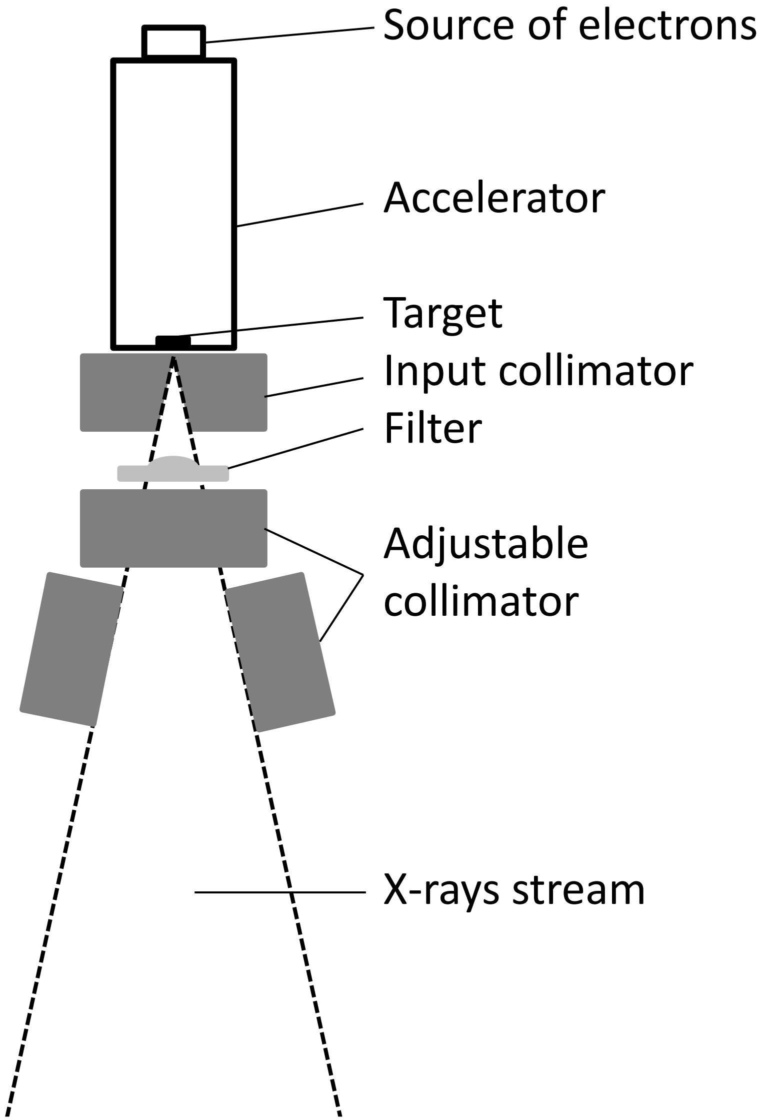
Nobel prize in physics in 1901

W.C. Röntgen, Sitzunggsberichte der Würzburger Physik-medic Gesellschaft, 1895
See also: Nature (1896) 274 trans. By A. Stanon

Principle of X-rays source



Accelerator NEPTUN – 10P



Electron energy 6, 8, 10, 12 MeV
e-/X converter; energy 6,9 MeV

X-rays generator

Accelerator

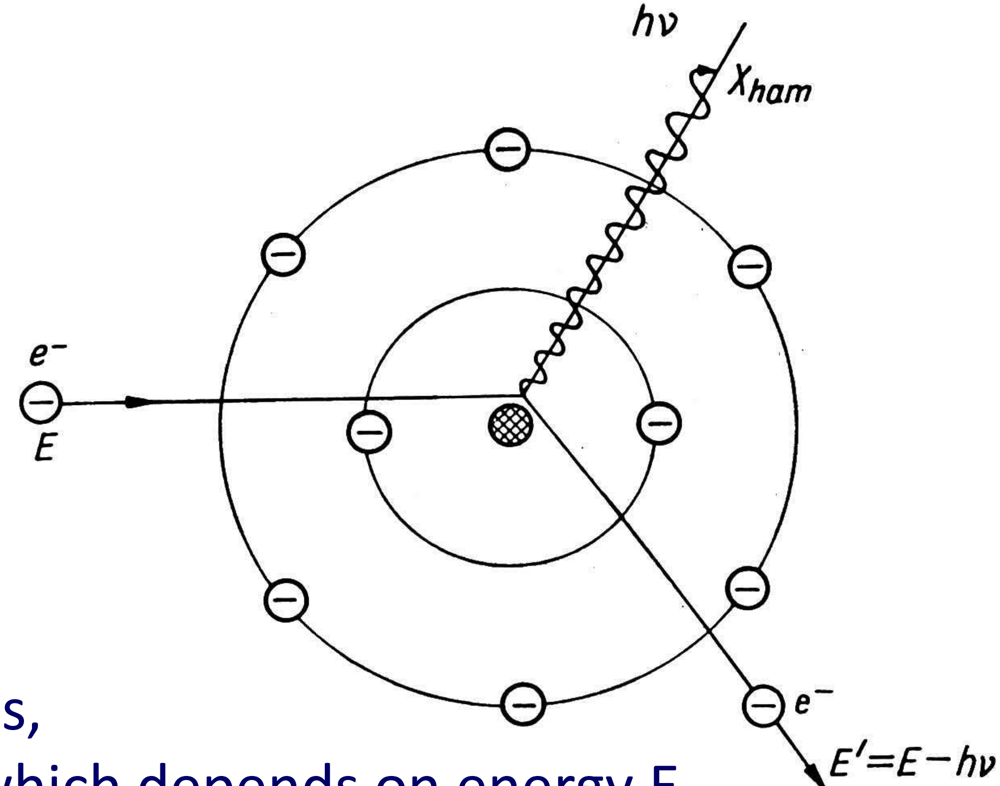
X-rays inspection

Electron beam / X-rays converters for radiation processing

- Physical properties of conversion process,
- Construction of electron beam / X-rays converter,
- Utilization of X-rays stream,
- Economical aspects of radiation processing based on X-rays application,
- Regulatory aspects.

Emission of photons in process of bremsstrahlung for the energy range 2 – 50 MeV

$$\frac{d\sigma_{br}}{dk} = C_r(E) f_E \left\{ \frac{d\sigma_{br}}{dk}(3BN) + \left[\frac{d\sigma_{br}}{dk}(3BS) - \frac{d\sigma_{br}}{dk}(3BN_b) \right] + W(E) \left[\frac{d\sigma_{br}}{dk}(3CS) - \frac{d\sigma_{br}}{dk}(3BS) \right] \right\}$$



k – photon energy,

E – kinetic energy of electrons,

$C_r(E)$ – empirical coefficient which depends on energy E,

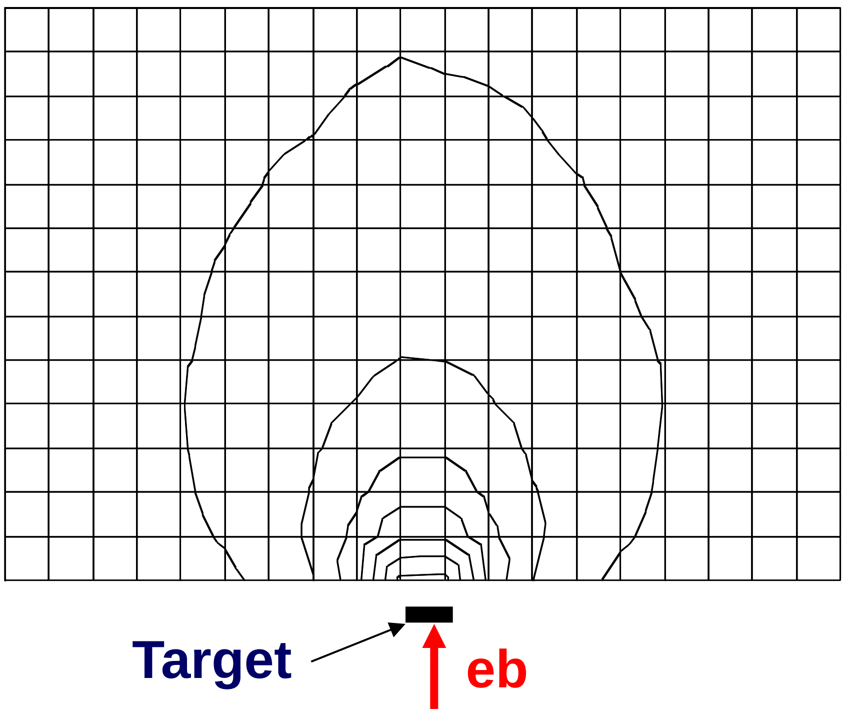
$f_E = \beta_o[1-e^{-2\pi Z/137\beta o}]/ \beta[1-e^{-2\pi Z/137\beta o}]$

$W(E) = 0{,}0011488E^2 + 0{,}0982E^2 - 0{,}190477$ [MeV]

Physical properties of conversion process

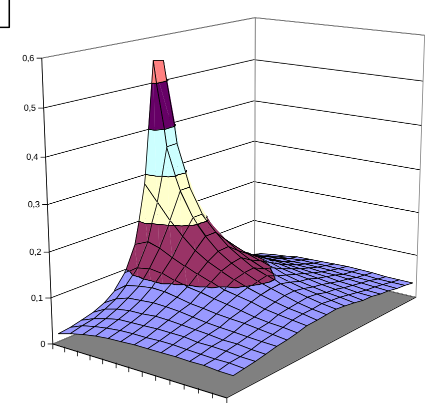
Spatial distribution of X-ray stream

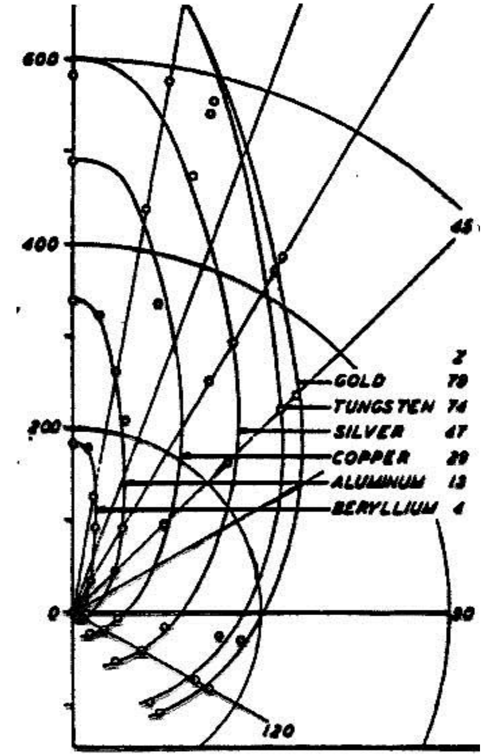
Tungsten target 0.8 mm thick



Electron energy 2.35 MeV
Forward x-ray 3.4 %
Backward x-ray 2.2 %
ModeXR computer code

X-RAY RELATIVE INTENSITY

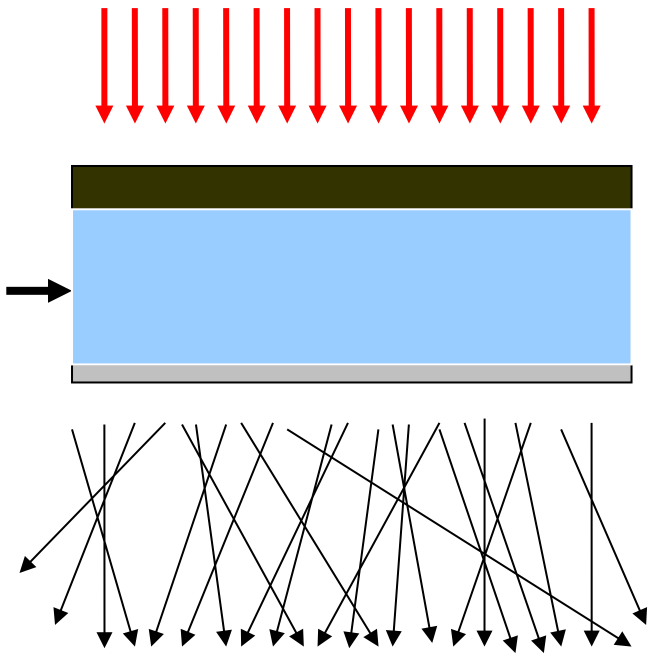




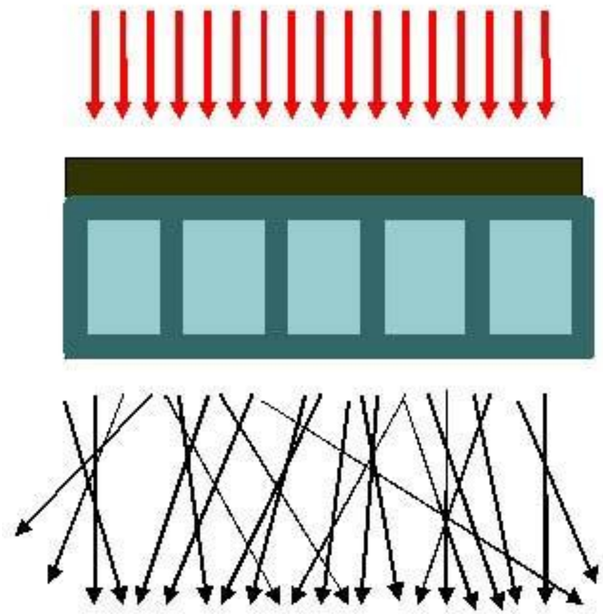
X-ray intensity as a function of angle for different target materials. Energy 2.35 MeV

W.W. Buechner, R.J.Van de Graaff, E.A. Burrill, A. Sperduto, Physical Review, v 74, No 10, 1948

Construction of electron beam / X-rays converter



- Electron beam
- Target: Ta
- Cooling water stream
- Stainless steel cover or Al structure
- X ray stream

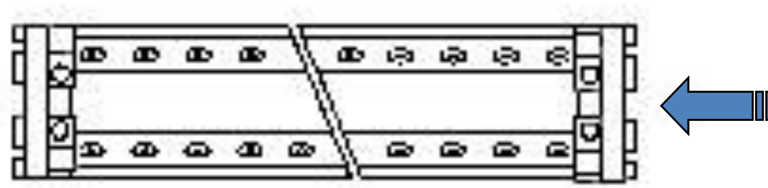


Target components (electron energy 5 MeV)		Energy deposited	X-ray transmmitted
Tantalum	0.8 mm	63 %	10.1 %
Water	10 mm	12 %	
Steel	1 mm	1 %	8.8 %

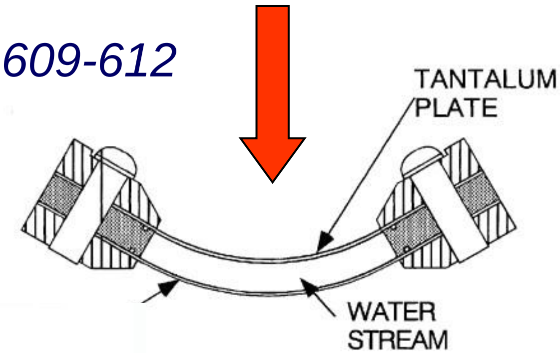
EB – X rays converter efficiency for different electron energy and Ta target with thickness 0,5 mm

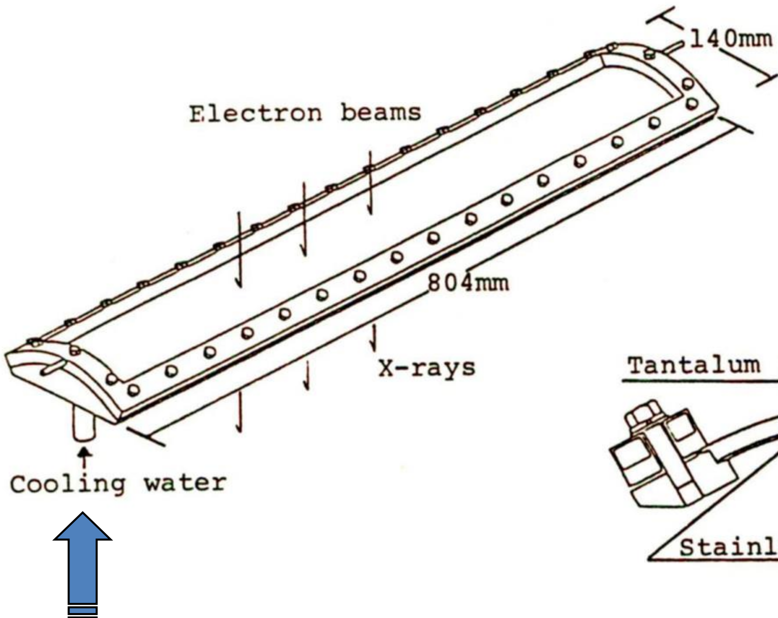
Ta target thickness		2 MeV	5 MeV	7,5 MeV	10 MeV
Transmis-sion	Electrons	0	0	0.00599	0.0879
	Photons	**0.0245**	**0.0754**	**0.0985**	**0.116**
Reflection	Electrons	0.242	0.111	0.057	0.025
	Photons	0.0158	0.024	0.015	0.008
Energy absorption	Ta 0.5 mm	0.442	0.406	0.226	0.141
	Water 20 mm	0.276	0.382	0.565	0.546
	Steel 0.8 mm	0.0012	0.0245	0.0398	0.088

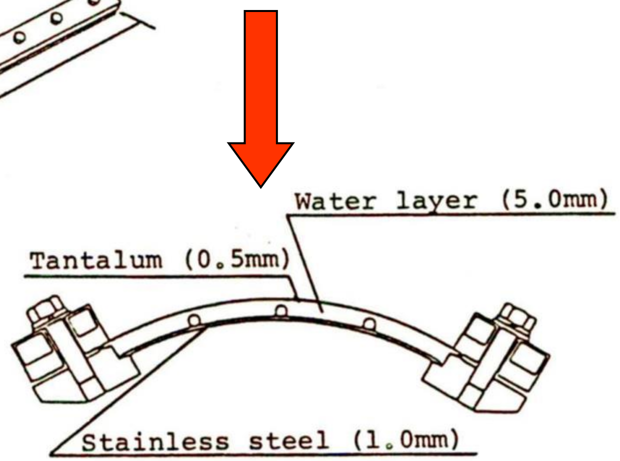
High power X-rays sources for radiation processing



Y. Aikawa, Radiat. Phys. Chem. 57 (2000) 609-612



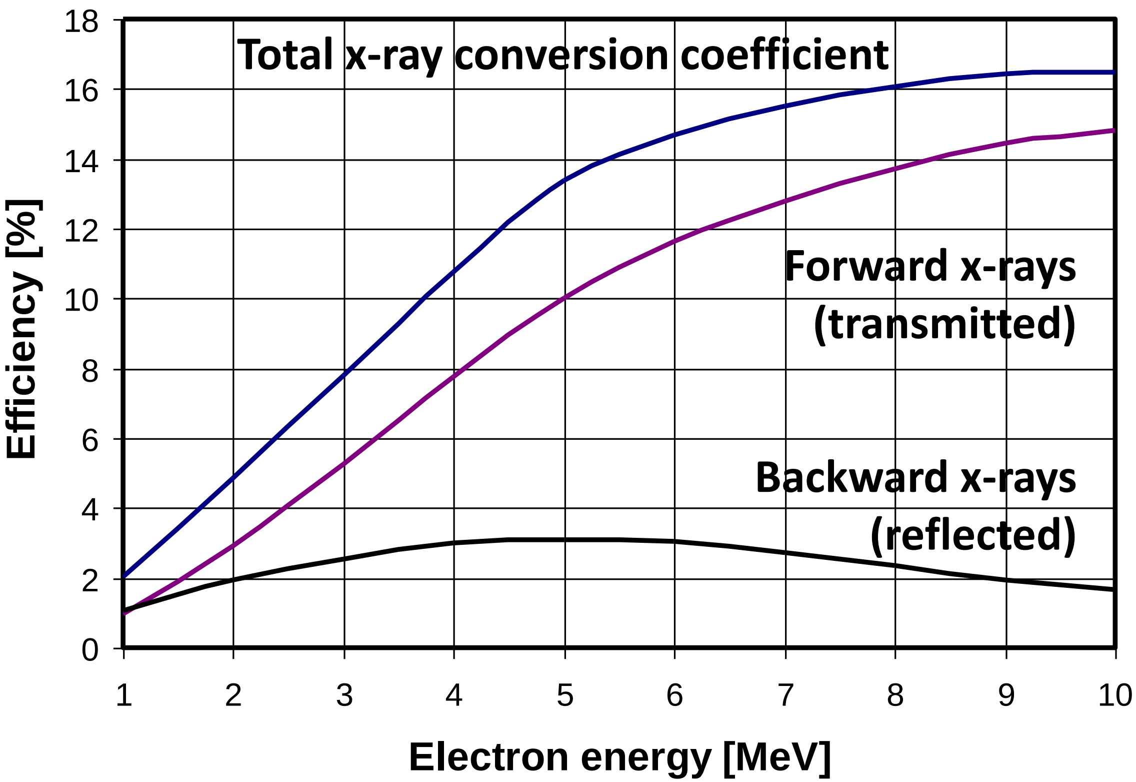




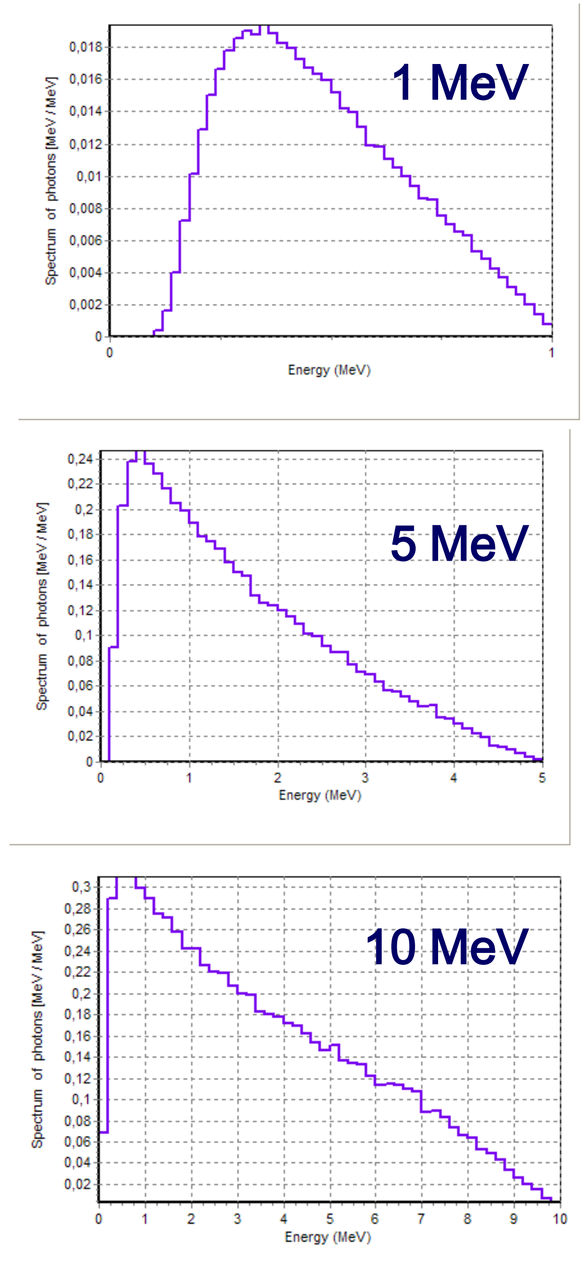
H. Sunaga et all, Proceedings of 3rd Japan-China Symposium, 1987

Physical properties of conversion process

Conversion process efficiency vs electron energy (Ta target)



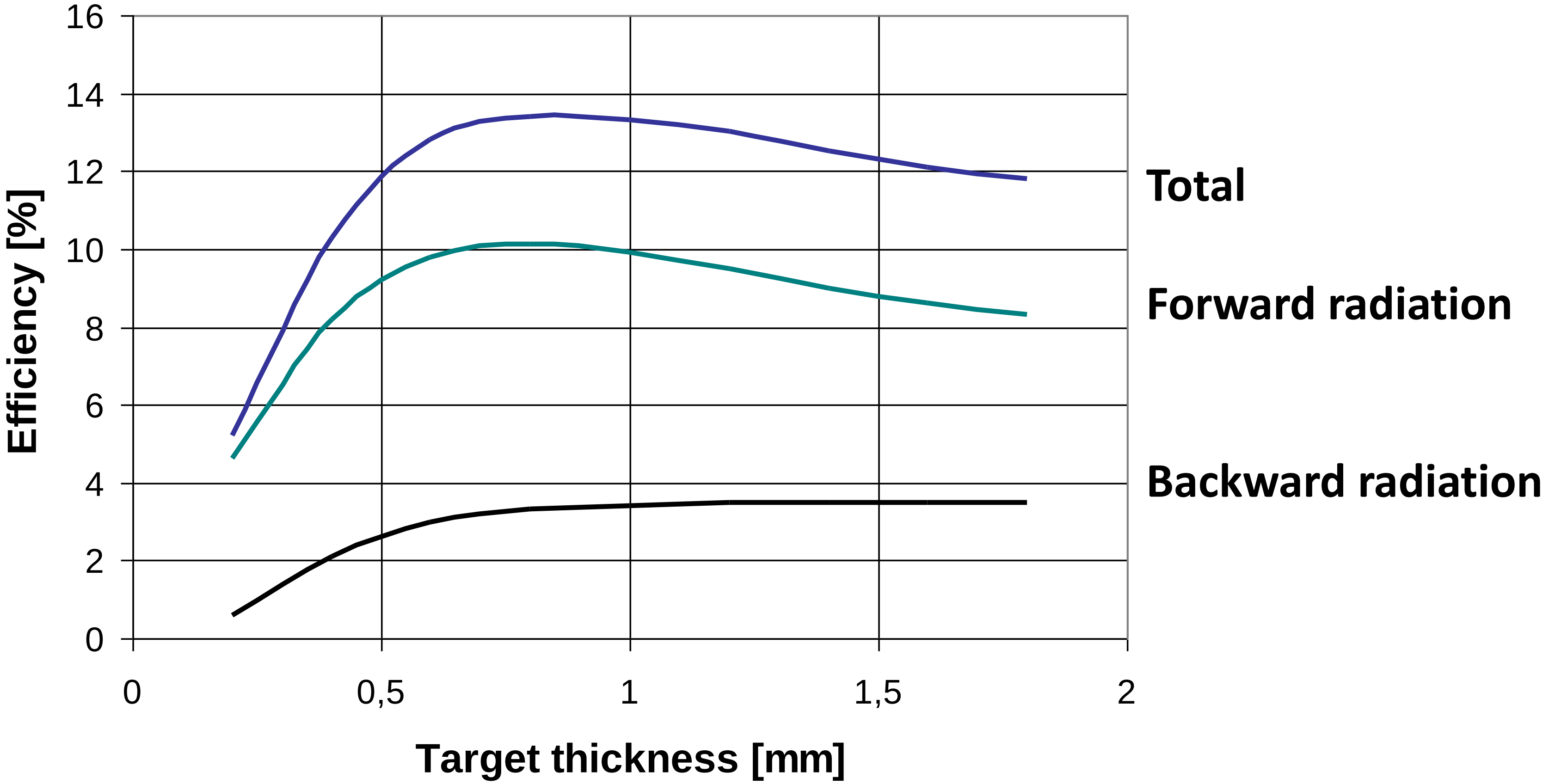
Target: Ta 0.8 mm thick



X-rays photons spectral distributions

Construction of eb / X-rays converter

Electron energy 5 MeV; Tungsten target

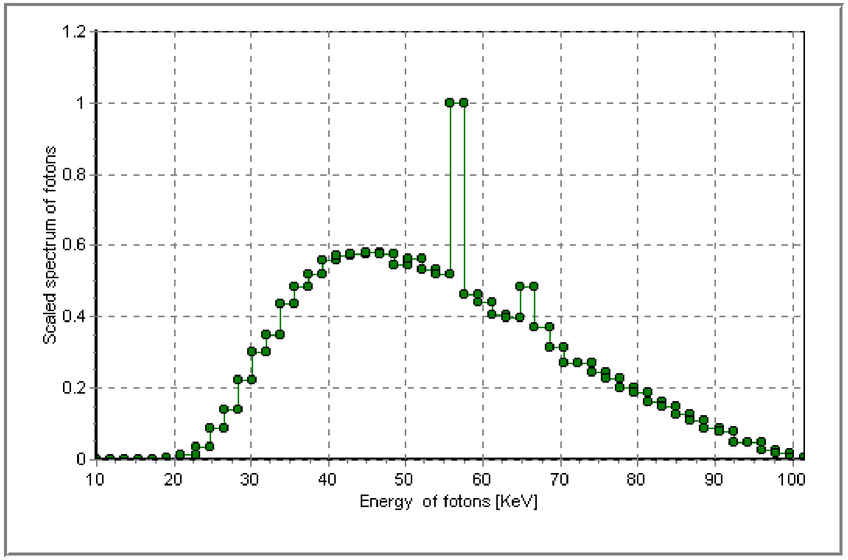


X-rays energy spectrum

U = 100 kV

w = 5,93 10^{-6}

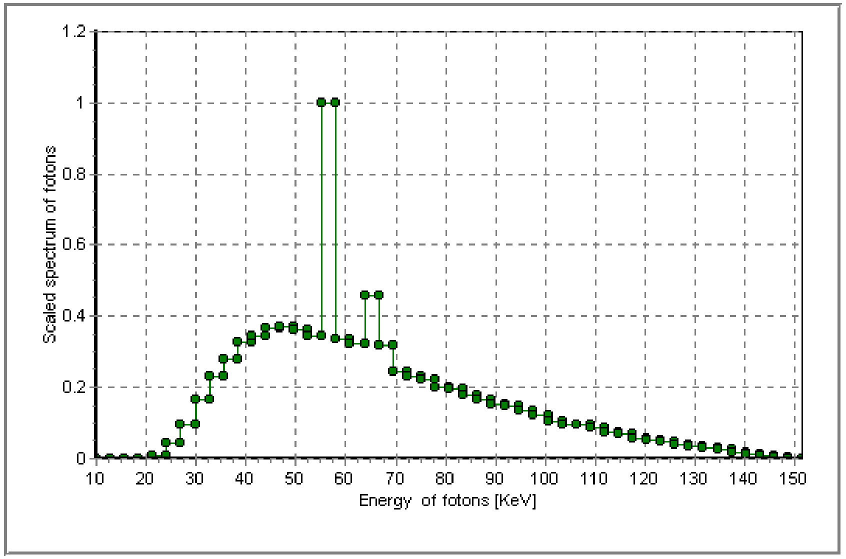
E_{av} = 54,3 keV



U = 150 kV

w = 1,63 10^{-5}

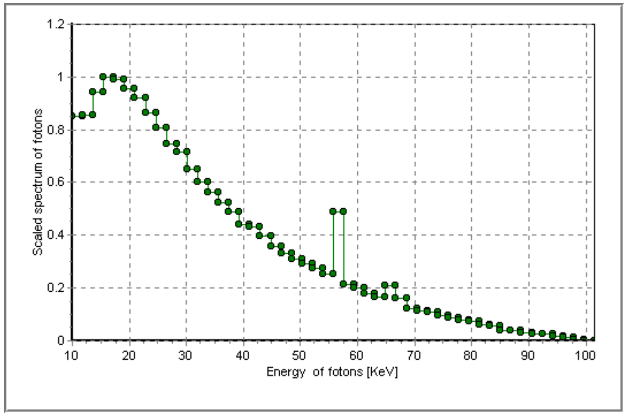
E_{av} = 65,7 keV



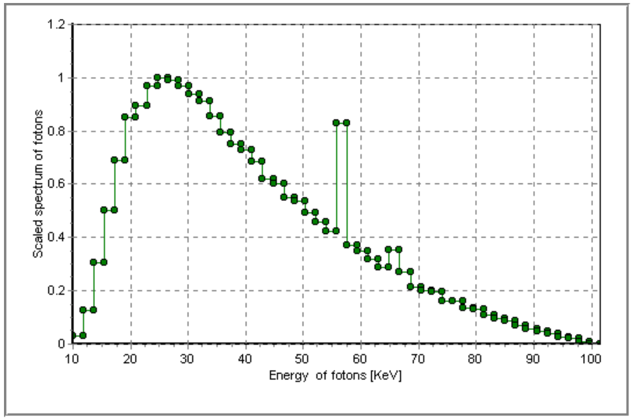
X-rays energy spectrum

Energy: 100 kV
Target: Ta 2 mm

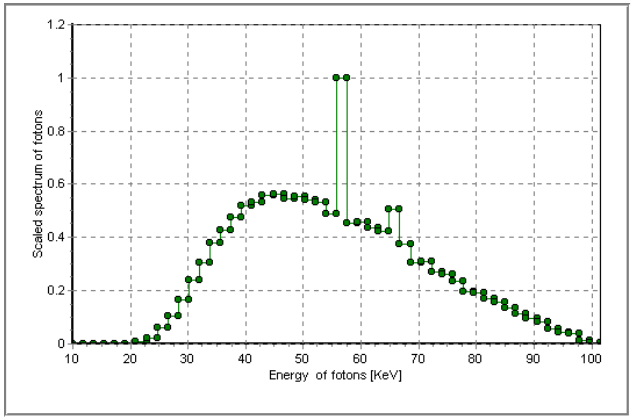
Ti window thickness:



0,01 mm



0,1 mm



1,0 mm

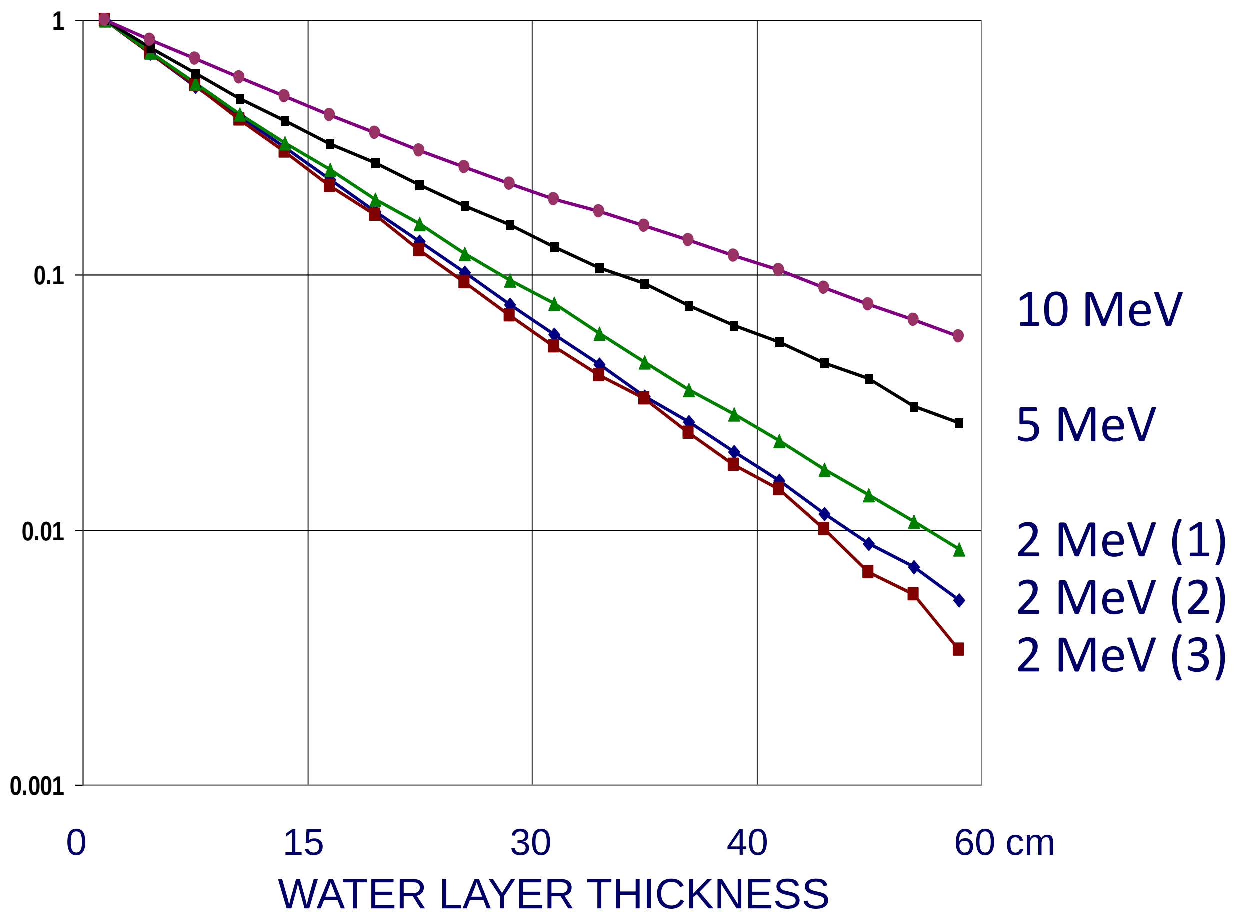
Depth dose distribution for X-ray irradiation with different initial electron energy level

Energy spread:

2 MeV (1)

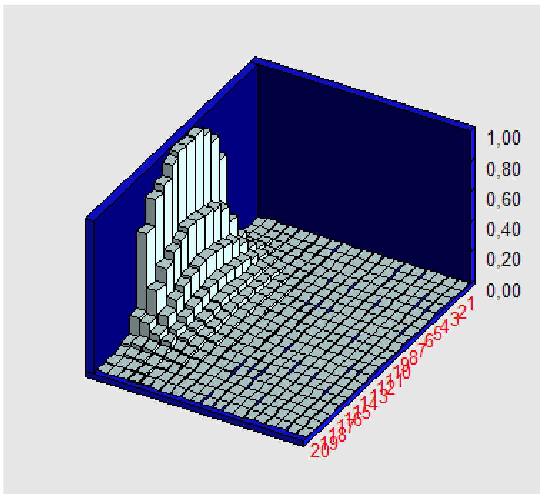
2.0 MeV x1.0
1.8 MeV x0.6
1.6 MeV x0.2 (2)

2.0 MeV x1.0
1.8 MeV x0.7
1.6 MeV x0.4 (3)
1.4 MeV x0.2
1.2 MeV x0.1

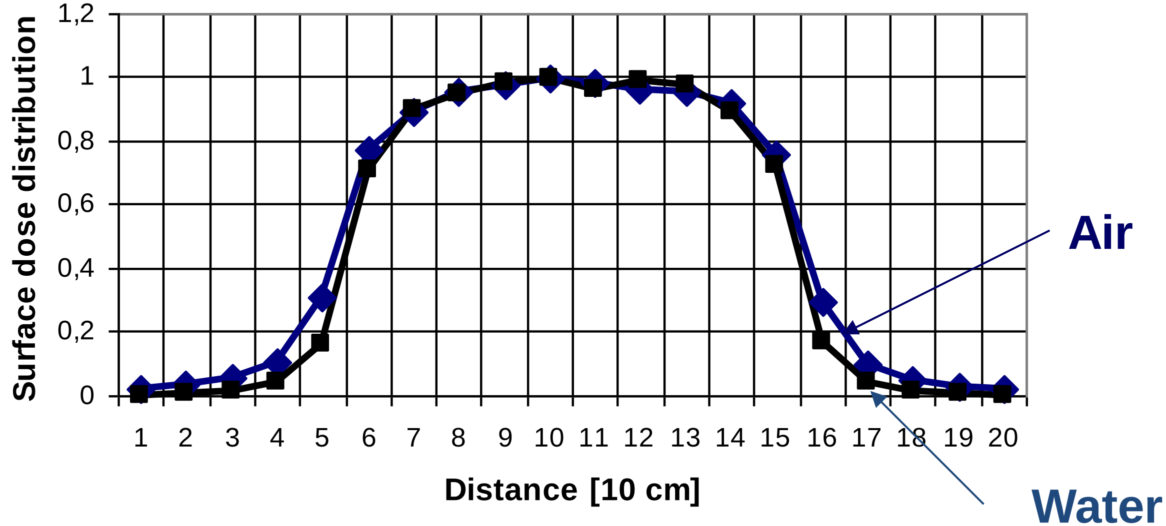


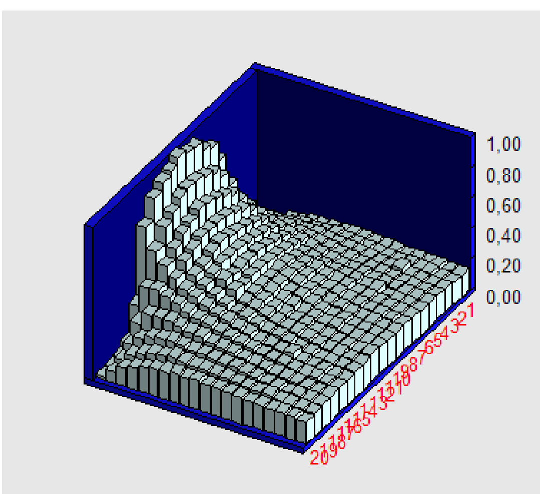
Utilization of X-rays stream

Conversion of scanned beam (5 MeV; Ta target 0.8 mm; scan 100 cm)

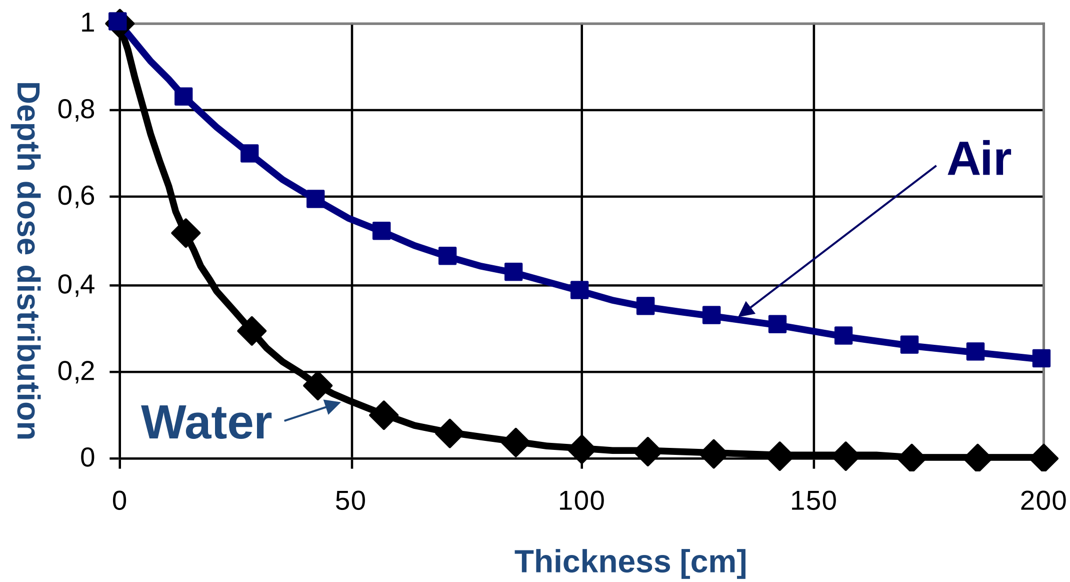


Water



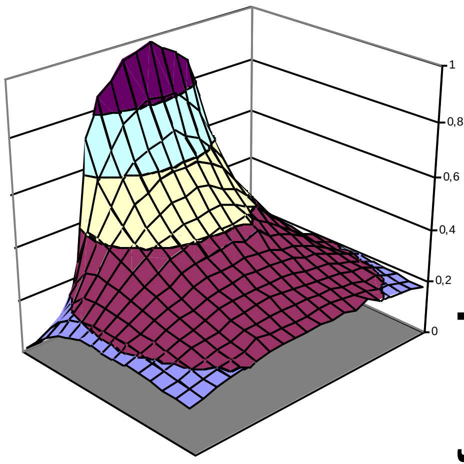


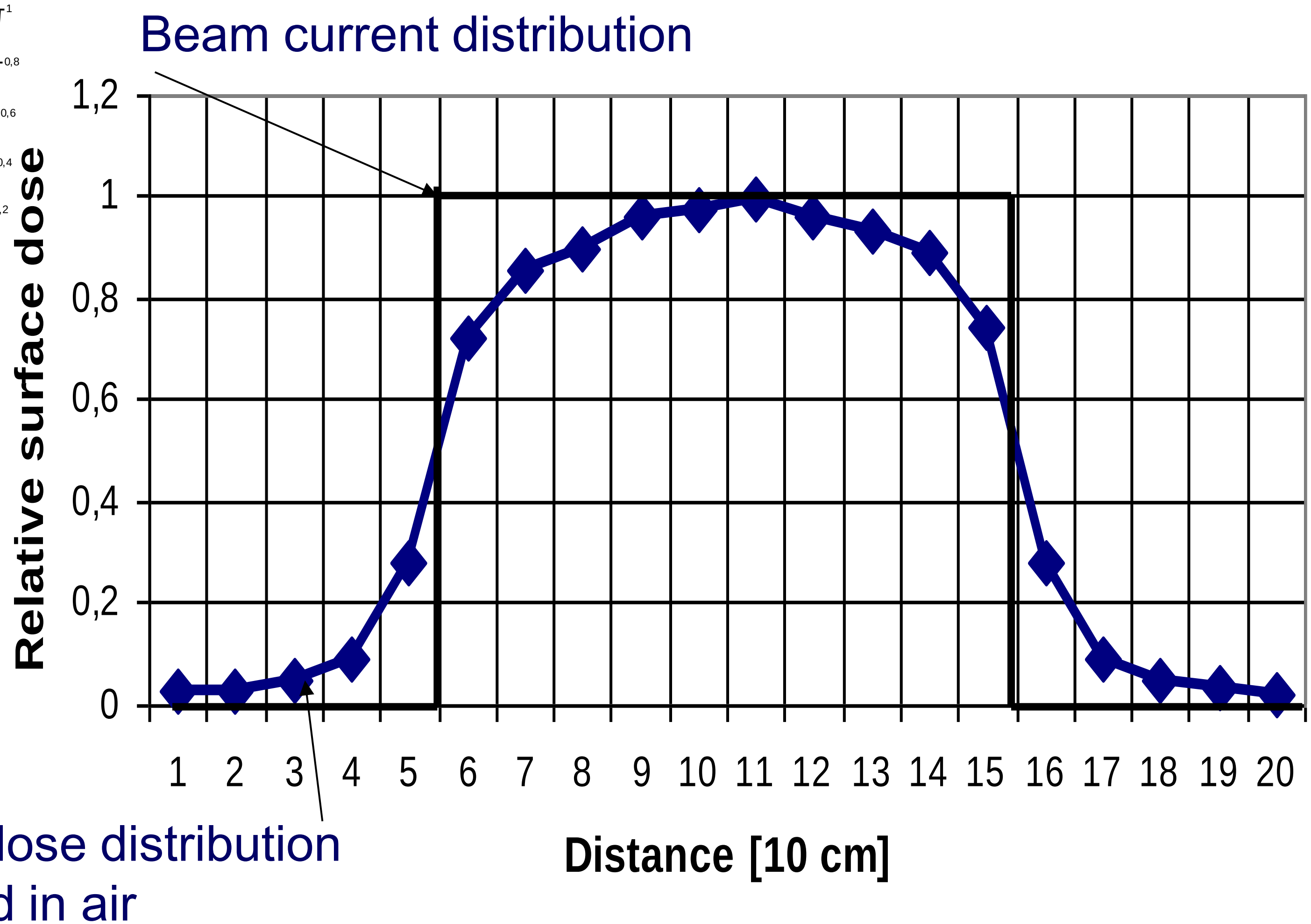
Air



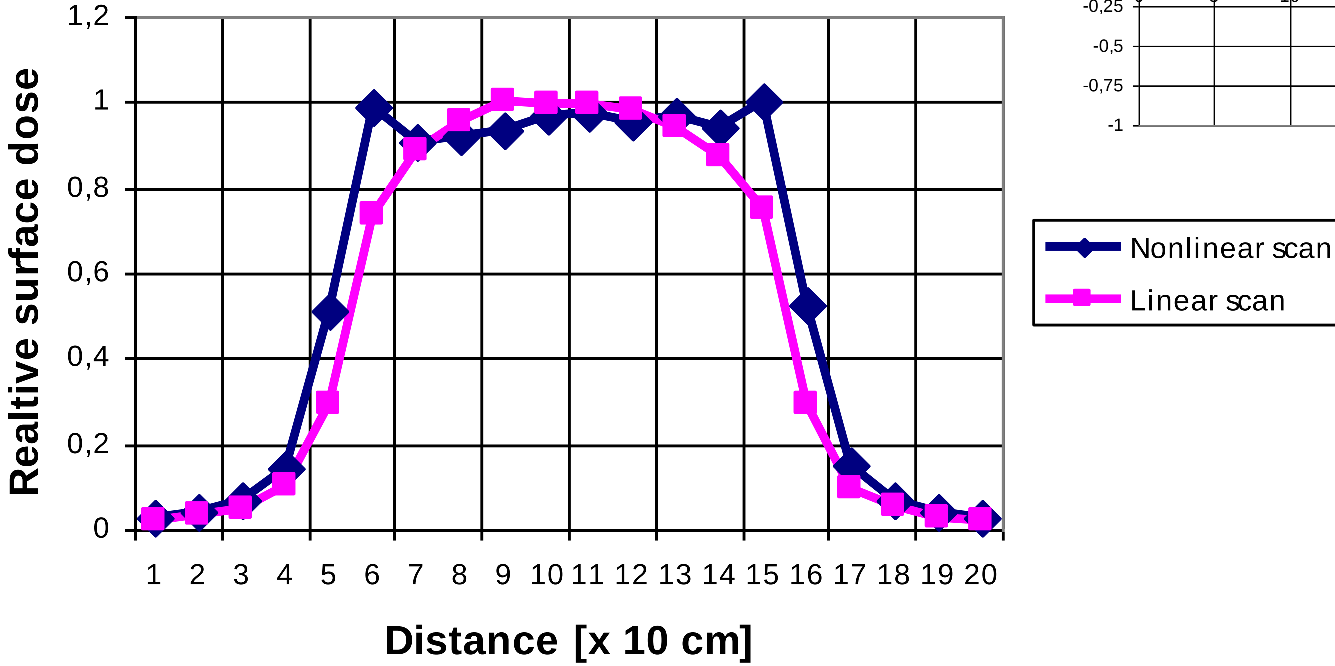
Utilization of X-rays stream

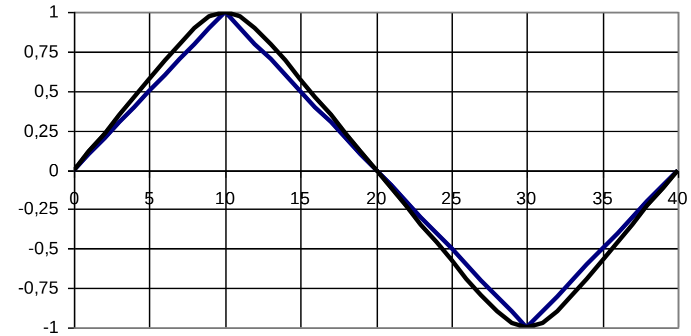
Conversion of scanned beam (5 MeV; Ta target 0.8 mm; scan 100 cm)





Utilization of X-rays stream



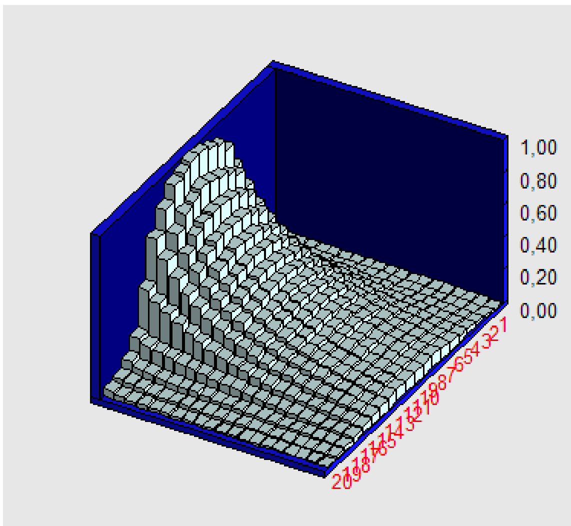


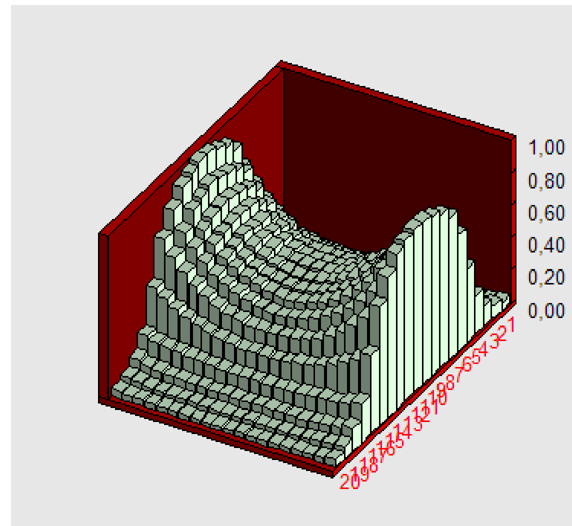
Surface dose distribution uniformity can be improved by:

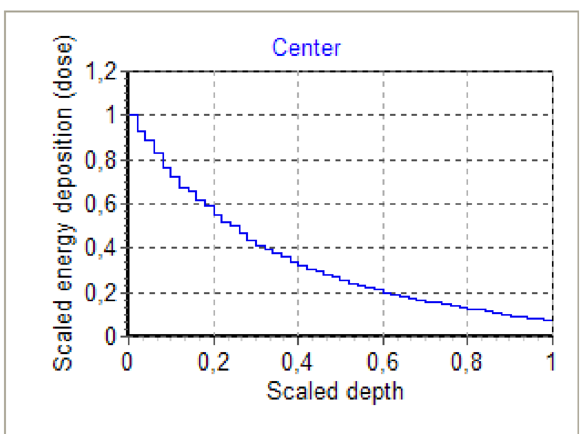
- Nonlinear current in scanning magnet (as it was described)
- Nonlinear beam current distribution *[V.L. Auslender et al. Radiation Physics and Chemistry 71 (2004) 279-299]*
- Nonlinear pallet rotation speed [*F.Stichelbaut et al. Radiation Physics and Chemistry 71 (2004) 291-295]*

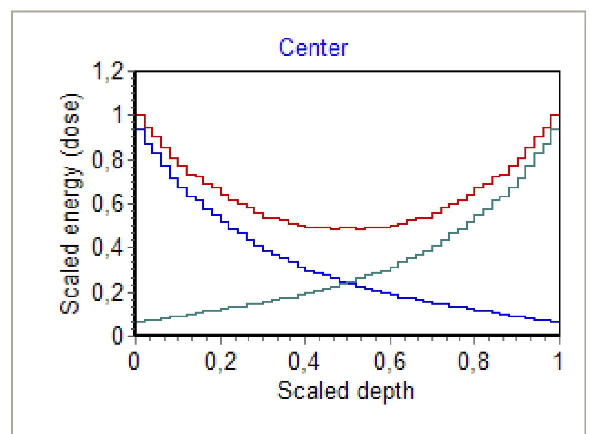
Utilization of X-ray stream

Conversion of scanned beam:
(5 MeV; Ta target 0.8 mm; scan 100 cm; water layer 40 cm)



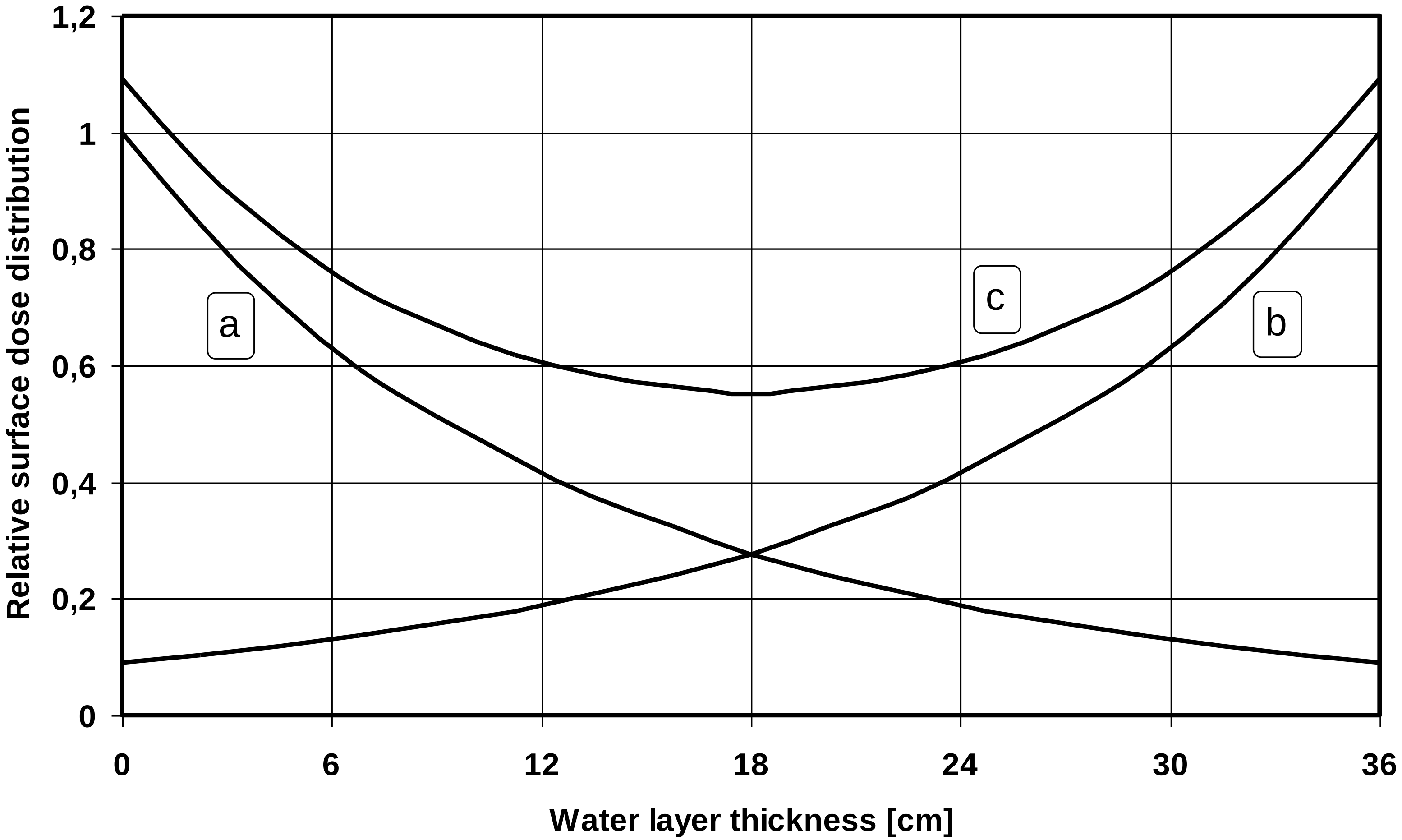






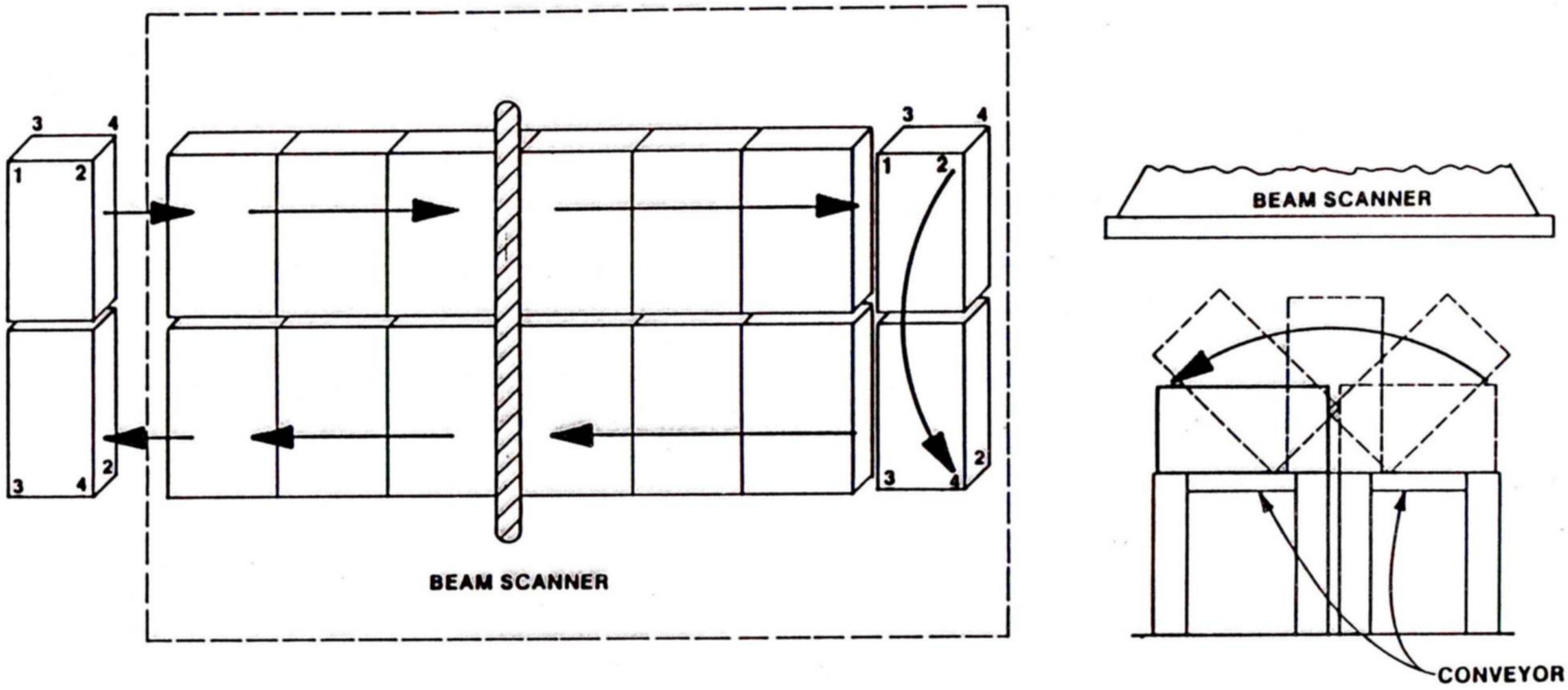
Utilization of X-ray stream

Double side irradiation process



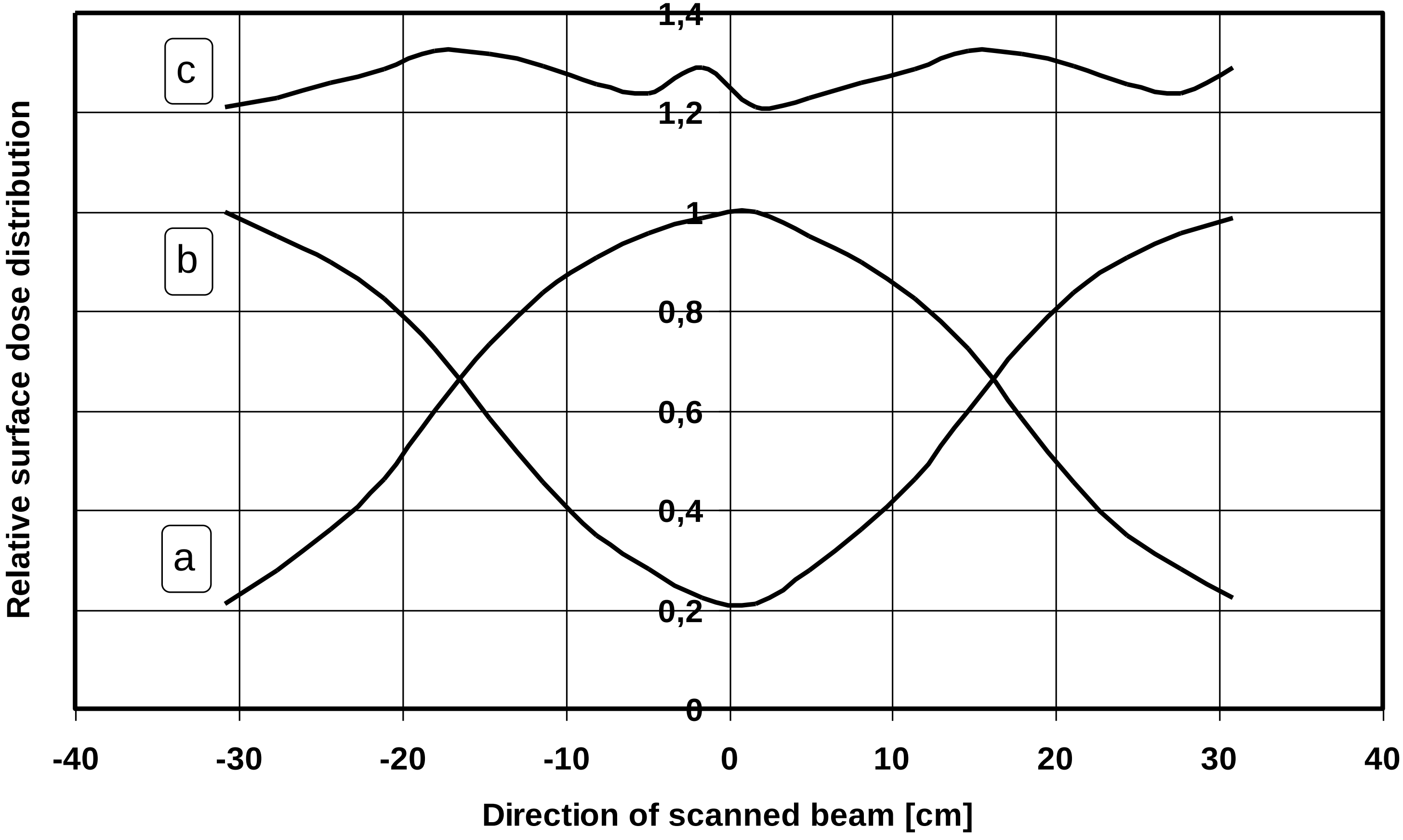
Depth dose distribution: a – top surface irradiation, b – botom surface irradiation, c – total dose distribution.

Four passes irradiation system



Utilization of X-ray stream

Four passes irradiation system



Surface dose distribution: a – first pass, b – second pass with 180^{o} rotation, c – total surface dose.

X-ray irradiation process

Radiation process productivity of the facility equipped with EB/x-ray converter can be calculated according to following formula:

Productivity [kg/h] = 3600 P [kW] η η_x / D [kGy]

Where:

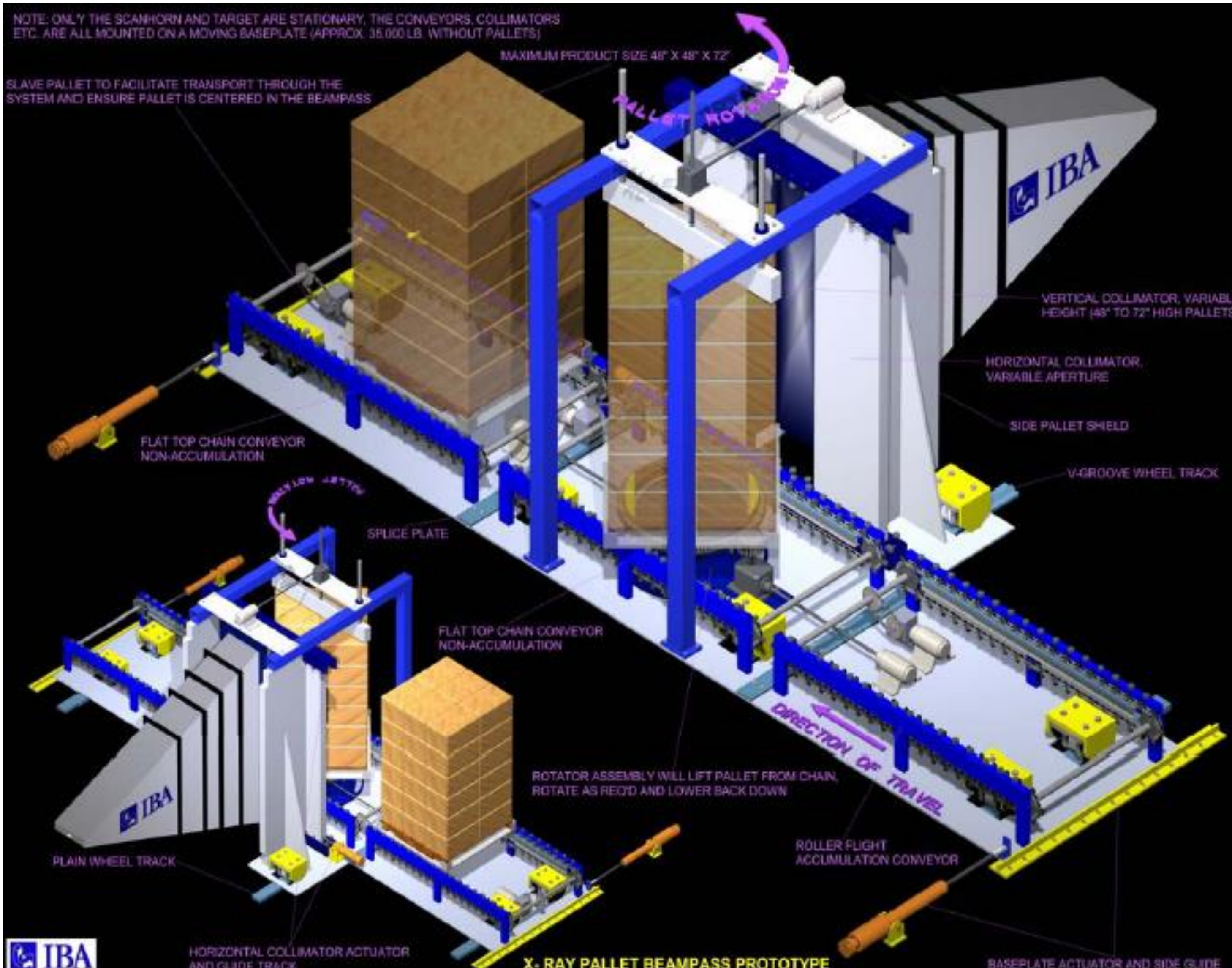
P – beam average power [kW]

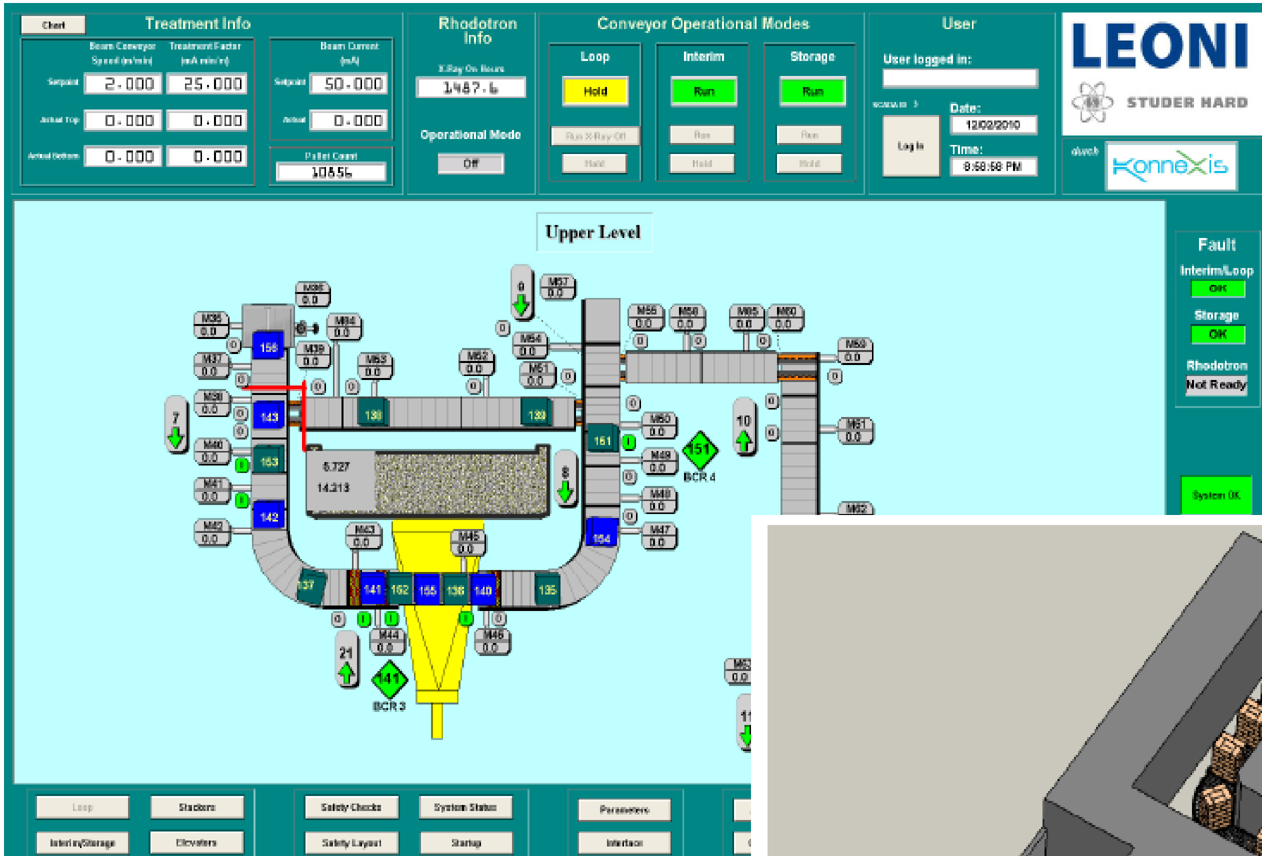
η – x-ray utilization coefficient (0.3-0.5 depends on irradiated product characteristic and acceptable Dmax/Dmin ratio)

η_x – conversion efficiency (0.05-0.07) depends on electron energy and converter construction

D – dose [kGy]

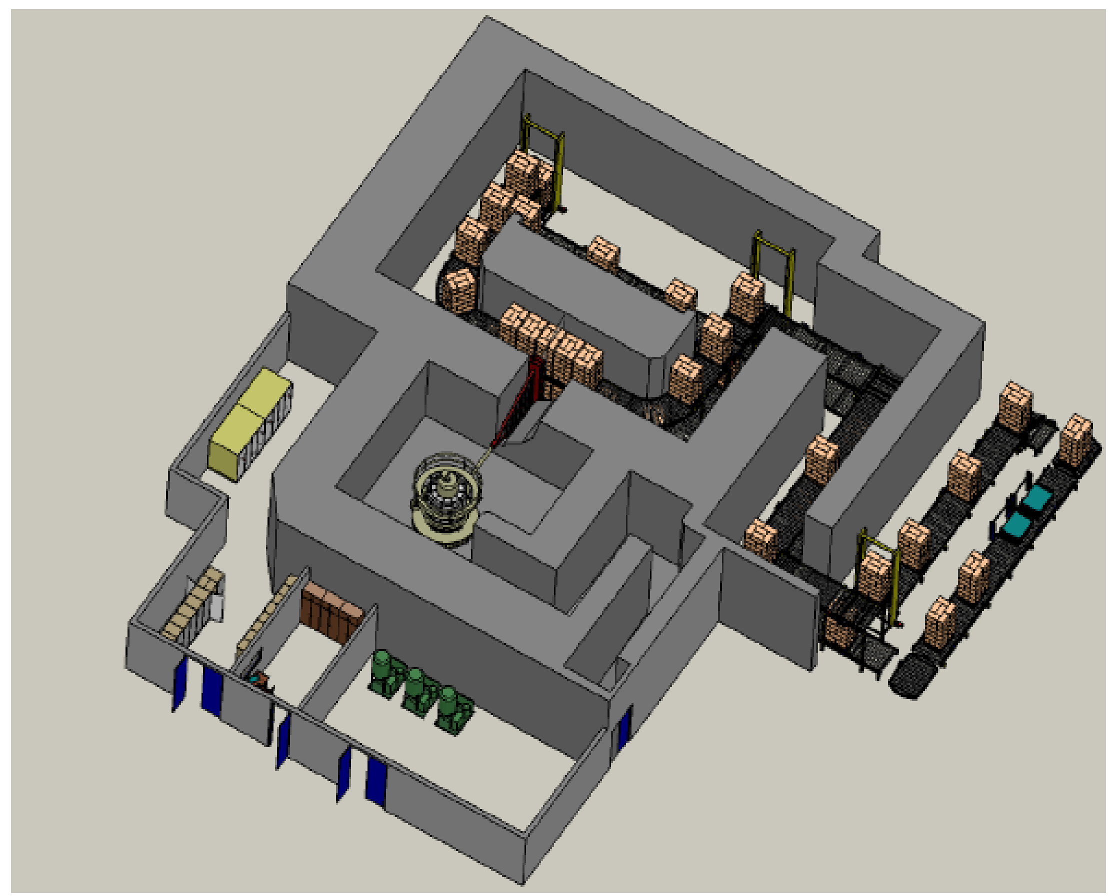
IBA PALLETRON™ ROTATIONAL METHOD





RHODOTRON, TT1000, IBA
7 MeV,560 kW

Gamma equivalent
4.4 MCi gamma Co60



X-Rays (Dose 25 kGy)
Product density:
0.15 gr/cc,
Productivity 560 kW; 7 MeV:
15.5 m³/h,
8000/rok (9% for service):
124,000 m³.

Radiological safety

- No suitable target material at electron energy 11 MeV and above due to ^{13}N activation,
- Stainless steel target can be accepted at 10 MeV,
- Tantalum target is acceptable at 7.5 MeV without the risk of production detectable activity of equipment and product with conversion efficiency nearly 50% higher that at 5 MeV.

J. McKeown et al., Radiat. Phys. Chem., 53 (1998) 55-61
O. Gregoire et al., Radiat. Phys. Chem., 67 (2003) 149-167
O. Gregoire et al., Radiat. Phys. Chem., 67 (2003) 169-183

- There are technical capabilities and economical reasons to apply x-ray radiation:

  - in research and R&D;

  - as supplement of EB processing in accelerators with electron energy 5 MeV and beam power 10-50 kW;

  - in facilities with high power accelerator (200-500 kW).

- Limitations are mostly connected to economy of x-ray application.
- X-rays facilities have been proved their competitiveness against gamma sources with activity higher than 1.5 MCi of ^{60}Co.

- Productivity in X-rays mode is about 15-20 times lower than in EB mode.
- Dose homogeneity in X-rays mode is very poor. It requires special conveyor arrangement (4 pass irradiation) or beam intensity correction along the scanner.
- Due to small productivity (high cost) and big penetration range there is no reason to apply X-rays in environmentally oriented applications.
- The computer codes have been developed as an effective tools for X-rays emission and absorption calculations.

Accelerator facility for radiation processing can offer:

- Electron beam ***only;***
- Electron beam ***or*** x-ray stream;
- Electron beam ***and*** x-ray stream;
- X-ray stream ***only.***

CONCLUSIONS: „Do we need X-rays?"

The right question is not ''Do we need X-rays?'' What should be taken into account:

- Clearance conformity,
- System flexibility, integration and availability,
- Investment cost,
- Treatment cost,

and then one can make the correct decision which source do we need.

T. Sadat, Radiation Physics and Chemistry, 71 (2004) 543–547

4. Comparison between eb, gamma, and X-rays facilities (advantages and limitations)

- **Electrons** from Particle Accelerators,
- **X-Rays** from Accelerated Electrons,
- **Gamma Rays** from Radioactive Nuclides,

but in absorbing materials, electrons, X-rays and gamma rays transfer their energies by ejecting atomic electrons, which can then ionize other atoms. All types of ionizing radiations produce similar effects.

The choice of a radiation source depends on the practical aspects of the treatment process, such as absorbed dose, material thickness, processing rate, capital and operating costs.

Radiation field distribution for eb, X-rays, and gamma sources

EB	X-rays	Gamma rays
Uni-directional and scanned	Most in forward direction	All directions
High dose rat	Low dose rate	Low dose rate
Short processing time	Long processing time	Long processing time
Single box process at a time	Sequence of single box processing	Several boxes processes together
Simple conveyor system	More complicated conveyor system	Complex conveyor system

Steps of decision:

- Which radiation technology has been selected,
- E-beam (limitation in penetration),
- Gamma ray (low dose rate - slow productivity),
- X-ray (less efficient for energy utilization).

Feature of EB processing

- EB gives its energy directly to the irradiated material
- It is not necessary to mix third material such as catalyst for chemical reaction.
- EB has very large capacity for irradiation process.
- Easy operation (Start/Stop)
- Easy maintenance

Radiation Technology	Electron Energy	Typical Penetration
Sterilization	3 –10 MeV	38 mm
Wire & Cable	0.4 – 3 MeV	5 mm
Shrink Film	300 – 800 keV	2 mm
Surface Curing	80 – 300 keV	0.4 mm

Radiation technology	Applications	Gam-ma	EB
Polymer modification	Electrical wires and cables	↔	↑
	Thermo-shrinkable tubes and tapes	↔	↑
	Curing of tire cord	↓	↑
	Artificial leather	↔	↑
	Foils for coating and packing	↔	↑
Sterilization Disinfection	Single use medical devices	↑	↑
	Preservation of spice, food	↑	↔
	Disinfestation of grain	↑	↔
Environmental protection	Flue gas treatment	↓	↑
	Water/wastewater treatment	↔	↑
	Sludge treatment	↔	↑
Others	Semiconductors	↓	↑
	Ceramic composites	↓	↑
	Surface treatment of fabrics	↔	↔

↑ EASY **↔ MODERATE** **↓ DIFFICULT**

GAMMA

- High penetration (Co-60) large volumes to be treated,
- Lower efficiency / higher dose uniformity,
- Throughput depends on the source activity, decreases in time because of the radioactive decay (necessary periodic upgrading),
- International transport of radioactive materials became difficult now.

X-RAYS

- Energy limited to 5 MeV (7,5 MeV in some countries),
- High penetration (slightly depends on energy),
- Low efficiency, better uniformity,
- Low throughput.

(Dual irradiators: e-beam – X-ray)

Physical Aspects of Radiation Processing

- **Penetration vs Electron Energy**
- **Electrostatic Charge Deposition**

Electrostatic charges are deposited by incident electrons which come to rest in thick materials.

The charge depositions are concentrated near the ends of the electron ranges.

The charge density decreases and the total energy deposition increases as the incident electron energy increases.

Required beam power:

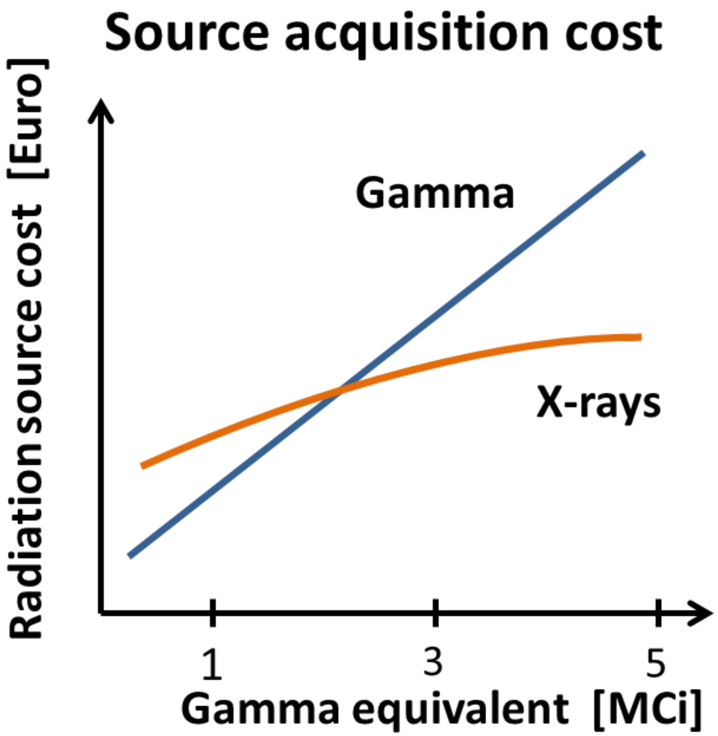
P [kW, kJ/s] = D [kGy, kJ/kg] x M [kg/s] / F

P – beam power [kW = kJ/s]
M – mass productivity [kg/s]
D – dose [kGy = KJ/s]
F – efficiency of beam utilization (0.2 – 0.7)

Type of Rhodotron		TT 1000	TT 400	TT 300	TT 200
Electron power	kW	560	290	190	100
Line power	kW	1230	660	450	260
Electricity cost per year	M$	1.18	0.63	0.43	0.25
Gamma Ci Equivalent	Mci	4.4	2.3	1.5	0.8
Cobalt load per year (2.5$/Ci)	M$	1.43	0.75	0.49	0.26

Assumptions:

- Electricity high @ 0.14 USD/kWh
- Electricity low @ 0.07 USD/kWh
- Cobalt-60 @ 3 USD
- 12.3% Cobalt decay/y
- 1 MCi treats 1 M ft^3 of pallets
- 1 kW treats 7800 ft^3 of pallets



X-rays technology comparison:

- Machine design as close as possible to the existing Gamma;
- Same product loading pattern can be used in both units;
- Minimal dose and maximal in the same zones;
- **Reduced treatment time compared to Gamma;**
- **Reduced overdose compared to Gamma;**
- **Reduced effects of ozone induced oxidation in the product;**
- **Indication of a much better dose usage for crosslinking application.**

Process validation issues:

- Process qualification with X- Ray is similar to Gamma and following the ISO 11137 standard.
- **Revalidation effort can be reduced for X- Ray treatment compared to gamma treatment as no source replenishments affecting dose distribution**

EB vs X-rays processing

- Productivity in x-ray mode is about 20 times lower than in EB mode,
- Dose homogeneity in x-ray mode is rather poor. It requires special conveyor arrangement like 4 pass irradiation or beam intensity correction along the scanner.

Advantages of X-rays over gamma rays

- Broader energy spectrum;
- More narrow angular dispersion;
- Greater penetration in materials
- More uniform dose distribution;
- Higher power utilization efficiency,

- X-ray source can be easily turned on and off;
- Save money when not need for production;
- Simplifies shipping, installation and maintenance procedures;
- Perceived to be less dangerous than isotope sources,

- New high power accelerator and target constructions,
- Growing data base regarding x-ray radiation processing,
- Difficulties with gamma sources production and transportation.

The options for sterilization by irradiation

Gammas from Co60

- Low investment cost, specially for low capacities;
- Simple and reliable, scalable from 100 kCuries to 6 MCuries;
- Isotropic radiation > inefficiencies in use;
- Pallet irradiation, but low dose rate > slow process;
- Absolutely no activation;
- Cannot be turned OFF > inefficient if not used 24/7;
- Growing security concern: the cobalt from a sterilization plant could be used to make dirty bombs.

Electron beams

- Directed radiation > Efficient use;
- Lowest cost of sterilization for large capacities;
- Can be turned OFF > safer;
- Short range (4.5 g/cm^2 at 10 MeV) > 2-sided irradiation of boxes;
- More complex dose mapping;
- Minimal, hardly measurable, but non zero activation.

X-Rays from E-beams

- Excellent penetration;
- Simple dose mapping;
- Pallet irradiation;
- Directed radiation > Efficient use;
- Loss of a factor 10 in energy when converting e-beams to photons;
- Cost of sterilization higher than electrons;
- Cost of sterilization is generally higher by X-Rays than Cobalt, excepted for very large capacities;
- Can be turned OFF > safer;
- Minimal, hardly measurable, but non zero activation.

Comparison of the 3 sterilisation technologies

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	Electron beam 10 MeV	Gamma Rays	X-Rays 7 MeV
Source	Electron beam	Cobalt 60	Electron beam with Target
penetration	Limited: one side about 400 mm at density 0.1	big (entire pallet)	big (entire pallet)
Homogeneity	Limited (dmx/dmin) about 1.5 (one side) to 2.8 (double side treatment)	Good: About 1.5 for pallets of about 400 kg	Very good: Better then 1.3 for pallets of about 400 kg
Treatment time	Seconds (very small lot under treatment)	Some hours (big lot under treatment)	Less hours (small lot under treatment)
Parametric release	yes	yes	yes
ISO 11137 accepted	yes	yes	yes
Tolerance for inhomogeneous loading pattern	small	good	Very good
unit	Box	Pallet	Pallet

Conclusions

- Gamma irradiation would be continue to be an important component of industrial radiation processing,
- Industrial electron irradiation would continue to grow for most of the current products,
- Area of major growth for electron accelerators are most likely to include environmental (water purification, sewage sludge irradiation, flue gas treatment), viscose and advanced composites,
- The availability of good variety of electron accelerators in wide energy range (40 keV – 10 MeV) is continue to grow of the radiation processing industry,
- Continued efforts to increase understanding and usefulness of the technology would also help to growth of this industry.