Radiation Processing with High-Energy X-rays

Marshall R. Cleland
IBA Industrial, Inc.
Edgewood, New York, USA

Frédéric Stichelbaut
Ion Beam Applications
Louvain-la Neuve, Belgium

CIRMS 2010
Gaithersburg, Maryland, USA
October 18-20, 2010

Presentation Outline

Introduction

X-ray Characteristics

High-Energy, High-Power X-ray Generators

Cost Comparisons of X-rays vs Gamma Rays

X-ray and Electron Beam Processing Facilities

A New X-ray Processing Facility
for Medical Devices

Conclusions

Introduction

Radiation processing is a method to change the physical, chemical or biological properties of commercial products and materials by treatment with ionizing energy.

In many cases, this technique can improve the performance and increase the market value of products treated with this method.

It can also be used to protect the environment from the deleterious effects of some toxic substances which can pollute the air, the water or the land.

Introduction

Examples of Radiation Processing

Curing inks, coatings and adhesives on metal, plastic, paper and wood substrates.

Crosslinking plastic film, foam, tubing and pipe, molded plastic parts, wire insulation and rubber components for automobile tires.

Sterilizing medical devices, disinfecting packaging materials and decontaminating fresh foods.

Curing carbon-fiber reinforced plastic materials and treating toxic waste materials - solid, liquid or gas.

Introduction

Practical sources of ionizing energy for radiation processing are accelerated electrons, X-rays emitted when energetic electrons strike heavy metal targets and gamma rays from radioactive nuclides.

All of these energy sources can create ions and free radicals, which can cause similar chemical reactions in irradiated materials.

The preferred type of radiation source is usually determined by practical process requirements, such as the minimum dose, dose uniformity and dose rate, material thickness, density and shape, production rates, capital and operating costs, and ease of use.

Introduction

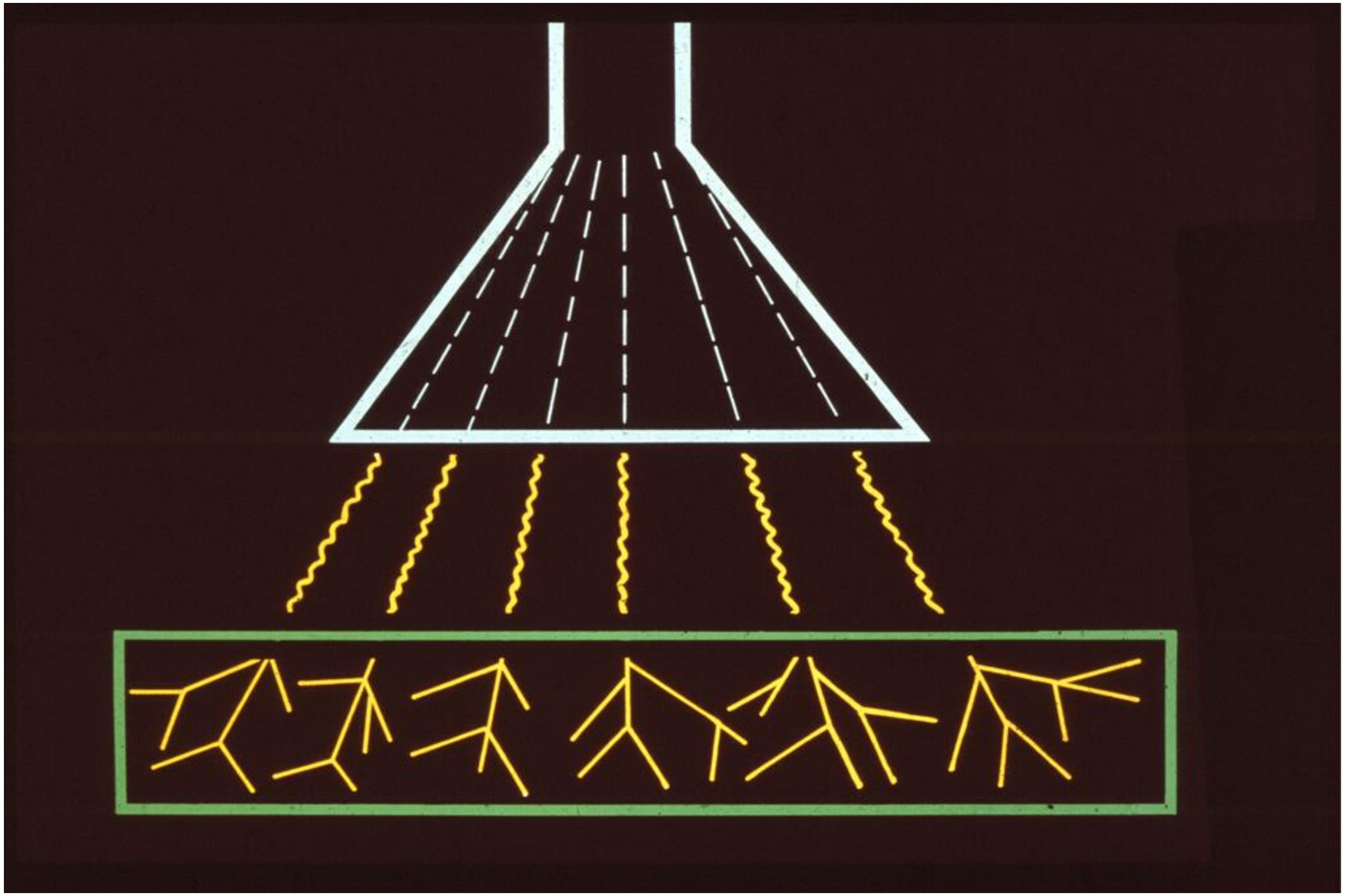
High-energy, high-power electron beams can process thin materials at high speeds, but their penetration is limited to a few centimeters.

Gamma rays emitted by cobalt-60 sources are mainly used to irradiate larger packages of medical devices and foods at slower processing rates.

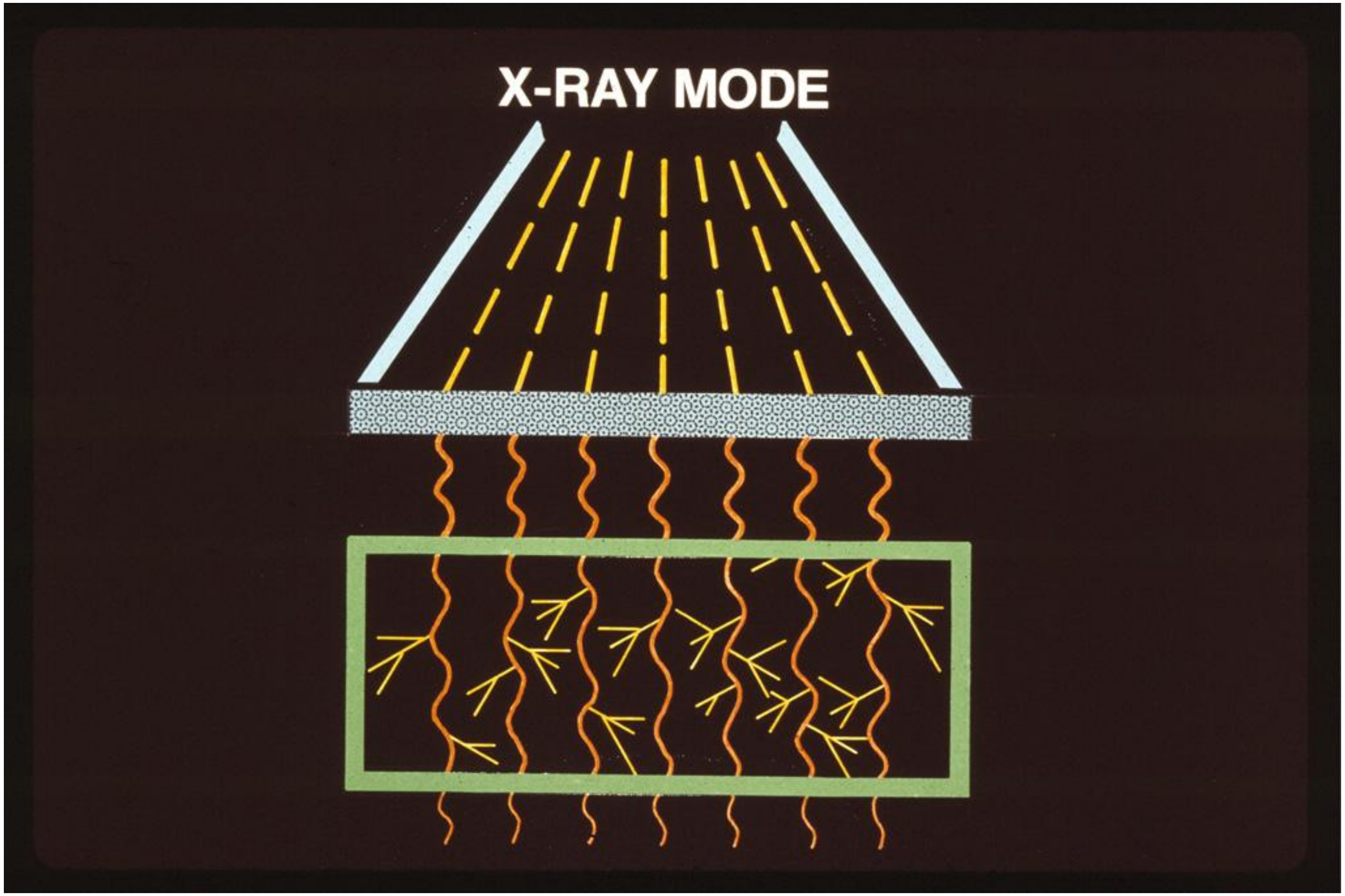
High-energy X-rays generated by electrons with kinetic energies greater than 3.0 MeV are more penetrating than such gamma rays.

Recent increases in the available X-ray power and in the price of Co-60 sources have made X-rays a viable alternative to gamma-rays for radiation processing.

Electron Beam Processing of Materials



X-ray Processing of Materials



X-ray Characteristics

Monoenergetic X-rays emitted by excited atoms are too low in energy and intensity for radiation processing. The maximum energy in uranium is only 116 keV.

Broad-spectrum X-rays (bremsstrahlung) generated by high-energy electrons have sufficient photon energy and intensity for these industrial applications.

With a 5.0 MeV electron beam, the most probable X-ray photon energy is about 300 keV, the average energy is about 1.2 MeV and the maximum energy is 5.0 MeV.

The forward bremsstrahlung intensity increases with the electron beam current, the electron kinetic energy, and the atomic number of the X-ray target material.

X-ray Target Materials

Broad-spectrum X-rays are emitted when high-energy electrons pass near atomic nuclei and are deflected by their electric fields.

Such X-rays are emitted when energetic electrons strike any material, but high-density metals with high atomic numbers make the best high-intensity targets.

Tantalum and tungsten are the most common target materials. Tantalum is better for high-energy electron beams because it has a higher threshold energy for induced nuclear reactions. It is also more ductile than tungsten and more suitable for making large targets.

X-ray Target Efficiencies

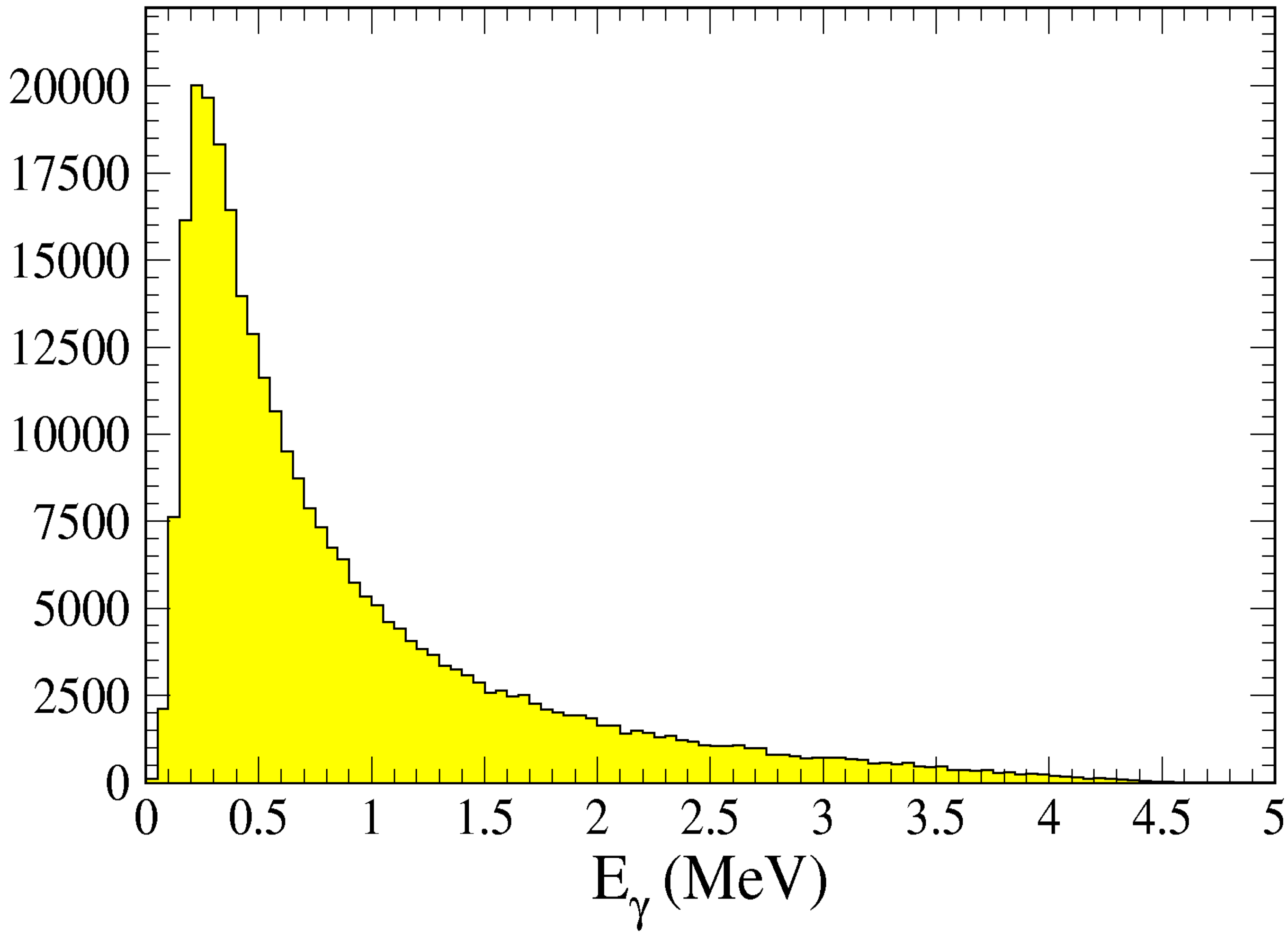
The highest X-ray yield can be obtained with a target thickness about 40% of the maximum electron range.

With 7.5 MeV electrons, the optimum thickness of a tantalum target is about 1.2 millimeters. A thin plate of stainless steel is placed behind the target to confine a thin layer of high-pressure, high-speed cooling water.

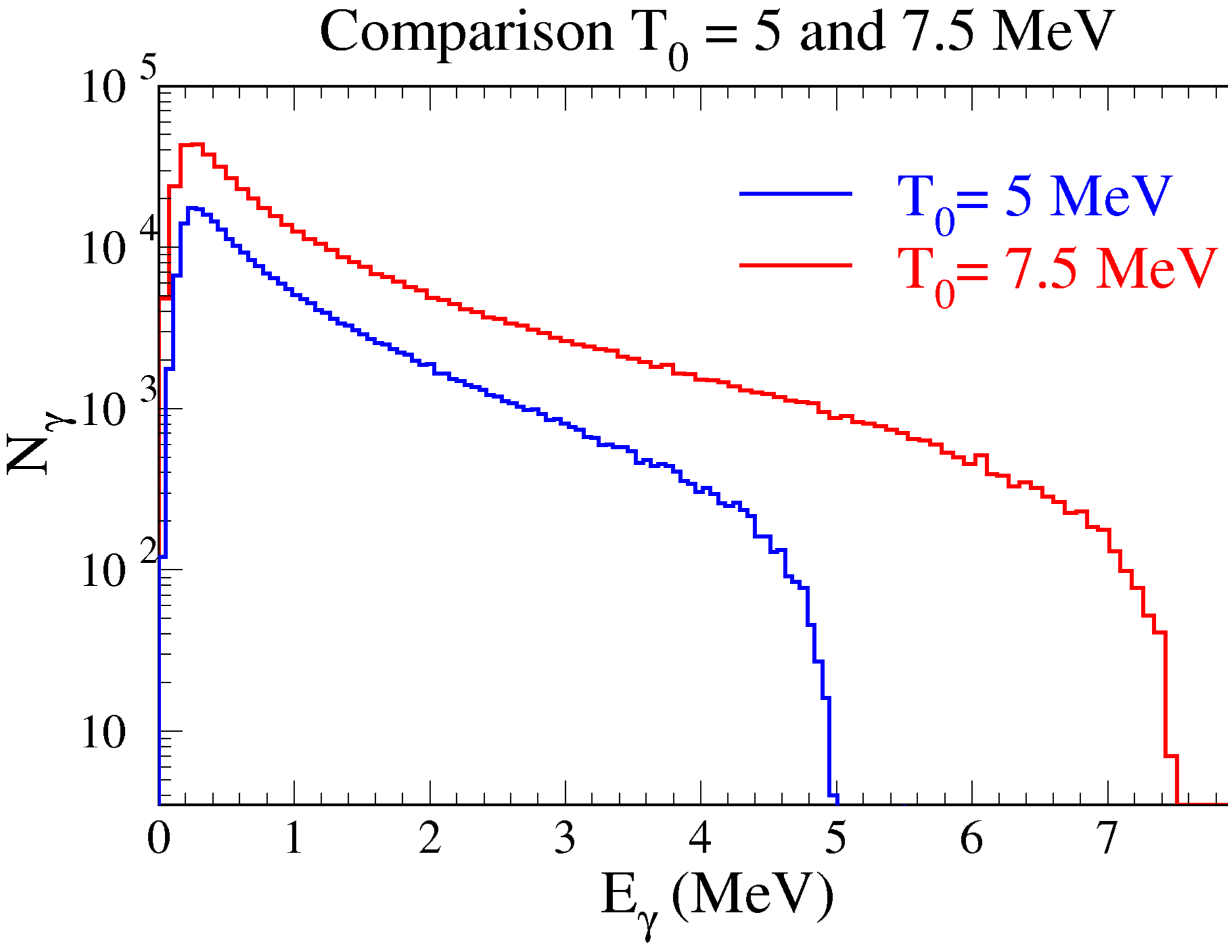
The efficiencies for converting electron beam power to X-ray power in the forward direction are approximately 8% at 5 MeV, 12% at 7.5 MeV and 16% at 10 MeV.

These relatively low efficiencies can be compensated by using high-power electron beams to produce X-ray dose rates sufficient for industrial radiation processing.

X-ray Photon Energy Spectrum – 5 MeV



X-ray Photon Energy Spectra – 5 and 7.5 MeV



Angular Distributions of High-Energy X-rays

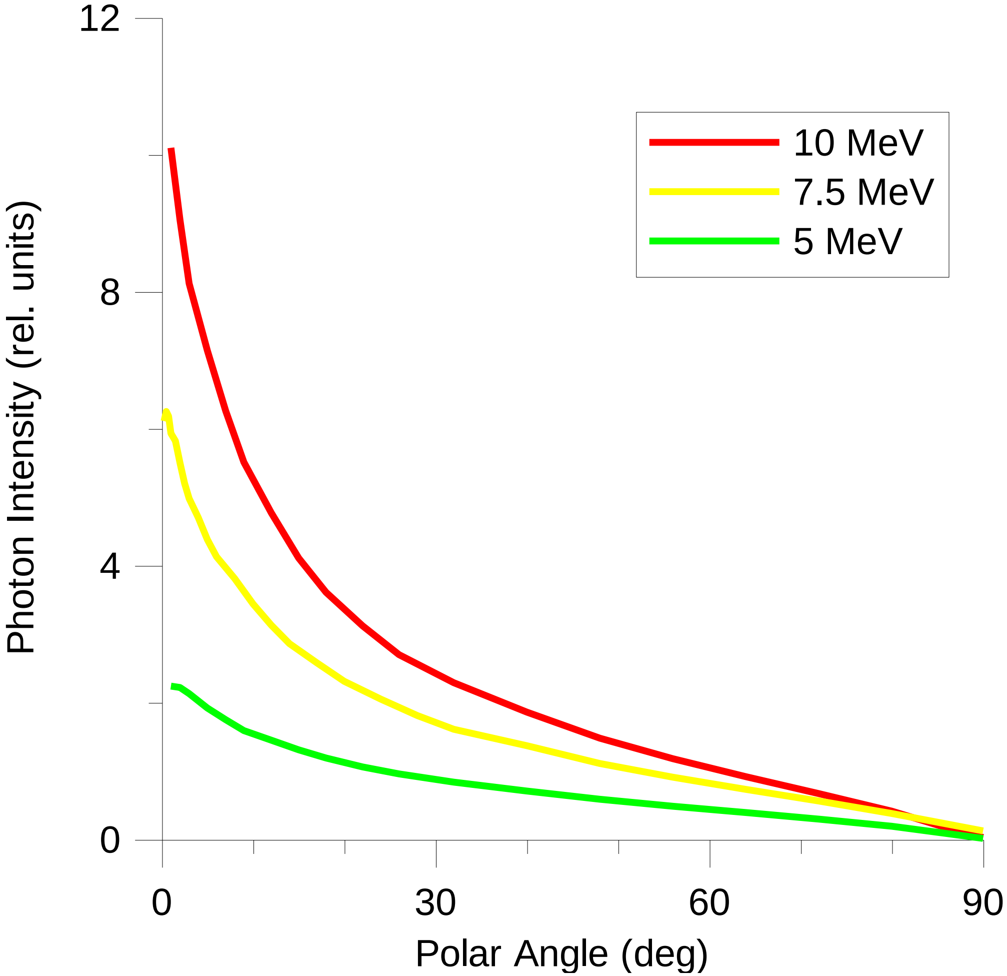
With electron energies above 2.0 MeV, the X-ray emission is greatest in the electron beam direction.

This characteristic is different from the isotropic emission of gamma rays from radioactive nuclides.

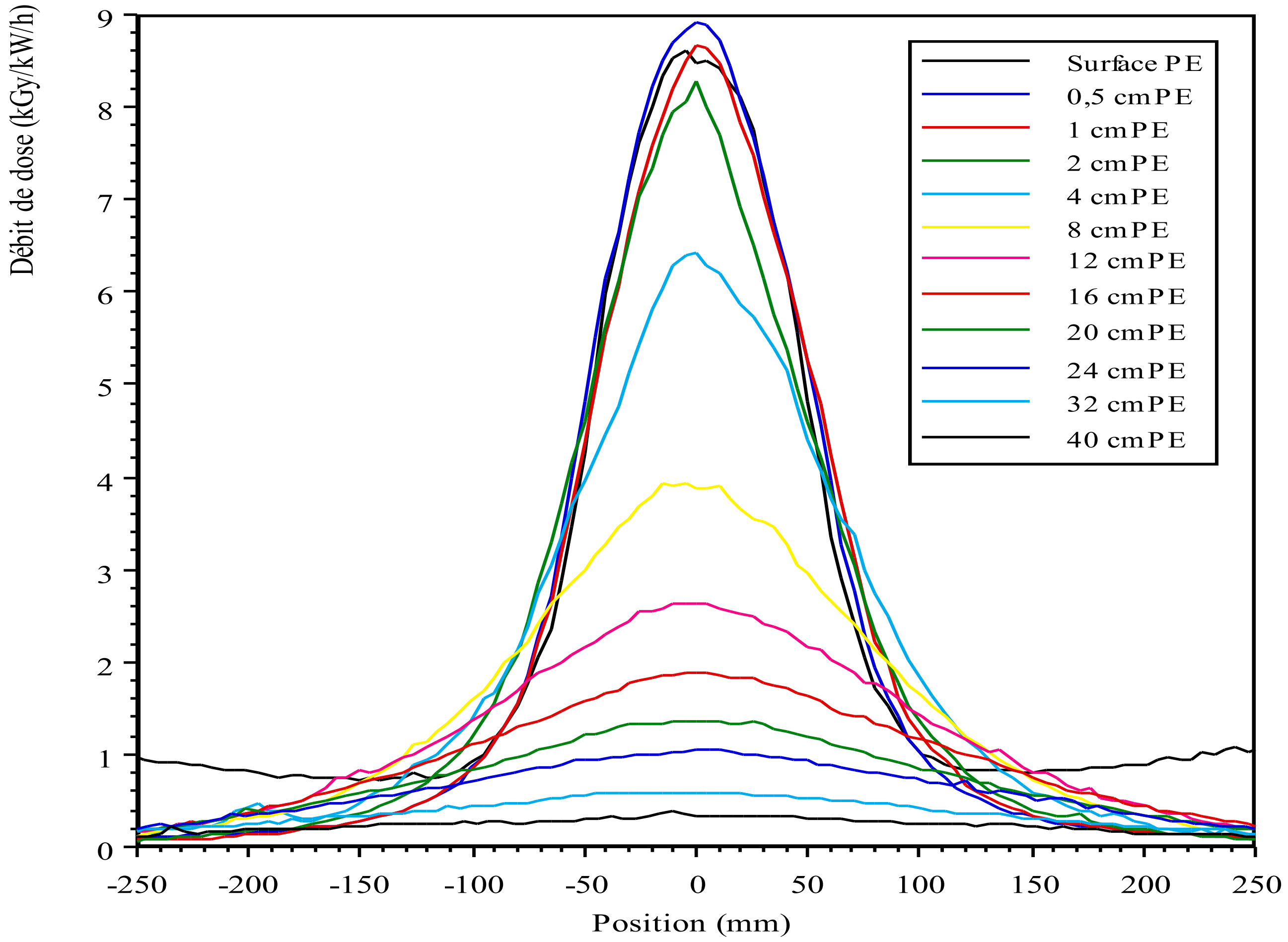
Their narrow angular distribution enables high-energy X-rays to penetrate deeper in irradiated materials and to be used more efficiently than gamma rays.

This makes it easier to manage changes in product density and dose requirements in an industrial facility for radiation processing.

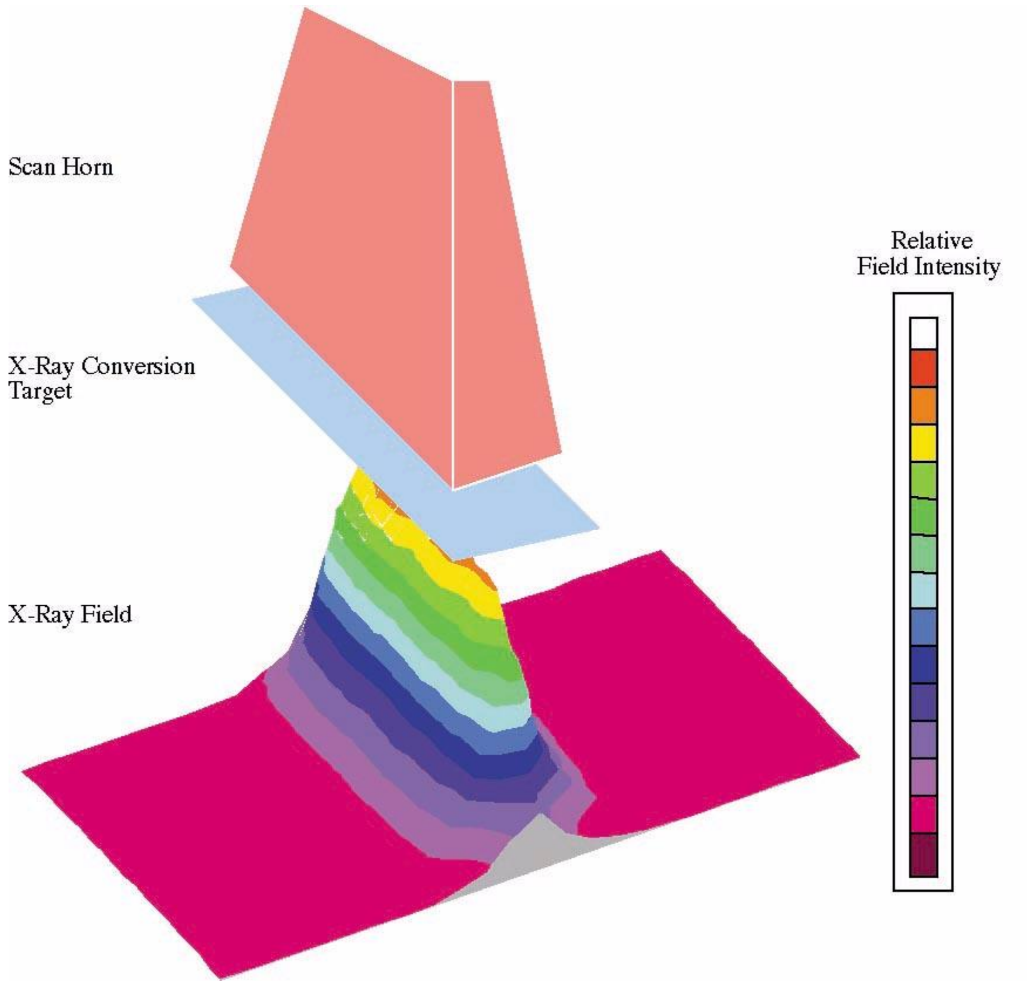
X-ray Angular Distributions



Lateral Distributions of X-ray Dose at 5.0 MeV



Three-Dimensional Picture of X-ray Dose vs Depth



X-ray Penetration in Processed Materials

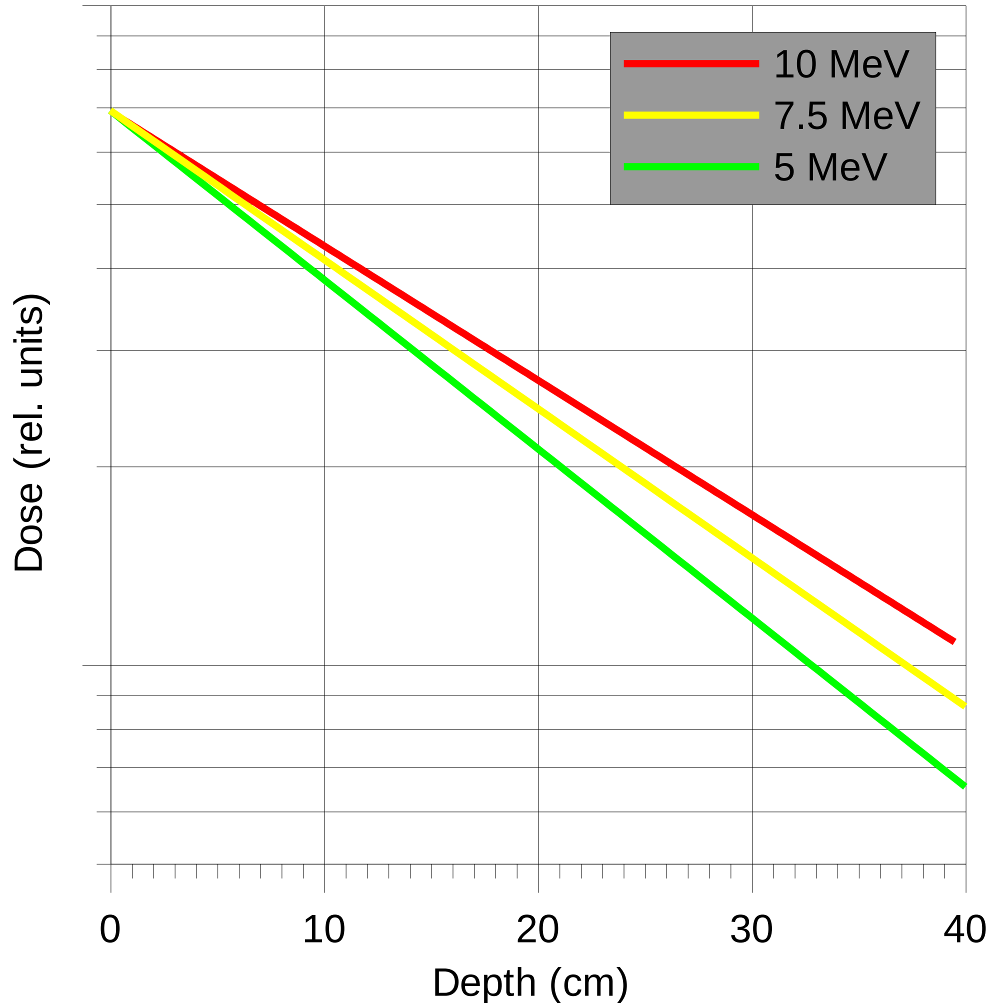
The X-ray intensities in processed materials decrease exponentially with increasing thickness.

The tenth-value layers in water and in most plastic materials increase with higher electron energy.

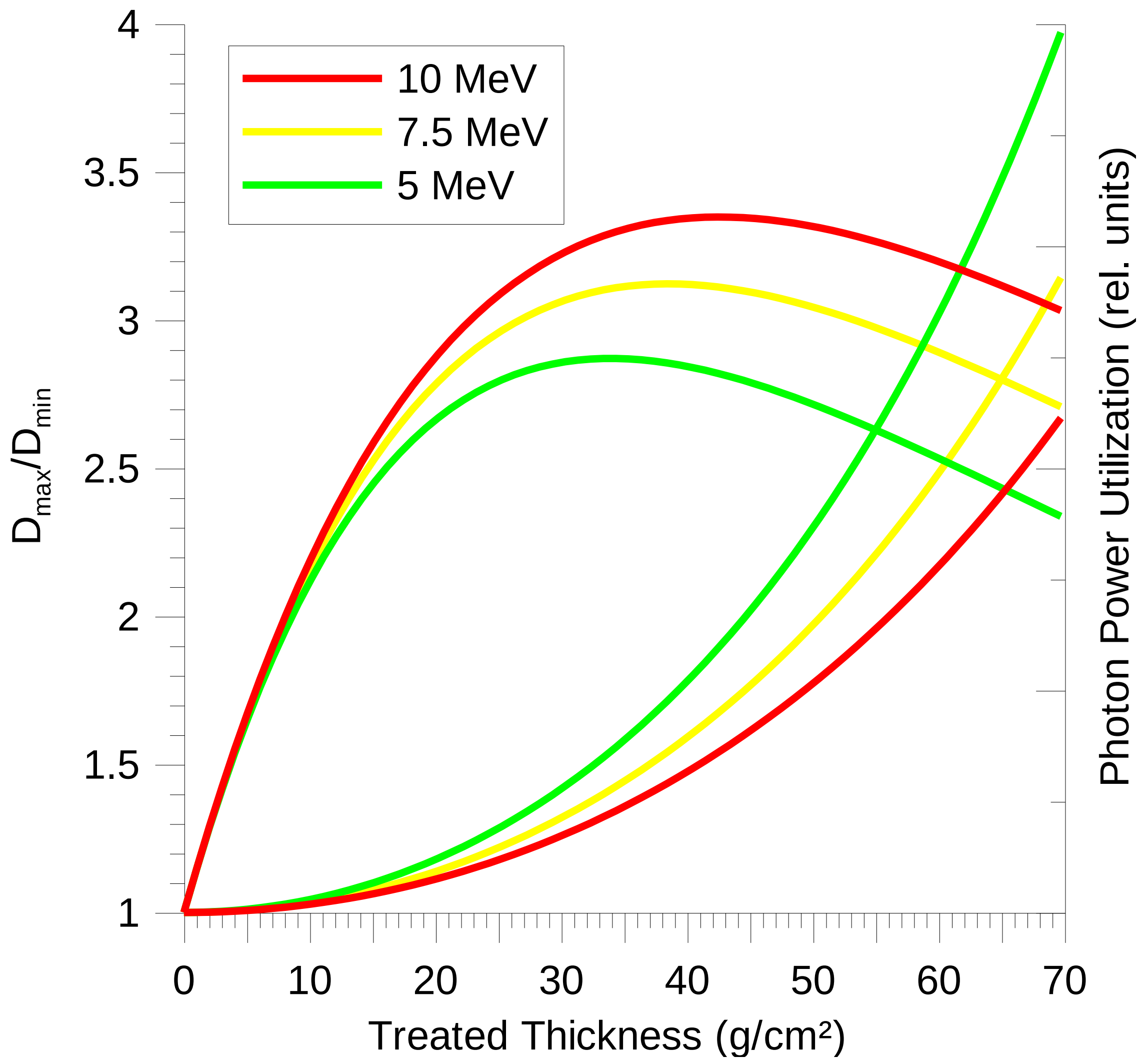
With electron energies above 3.0 MeV, the tenth-value layers for X-rays are more than for Co-60 gamma rays.

For irradiation from opposite sides, the optimum thicknesses for the most efficient use of X-ray power increase with higher electron energy. The optimum thicknesses for high-energy X-rays are greater than for Co-60 gamma rays.

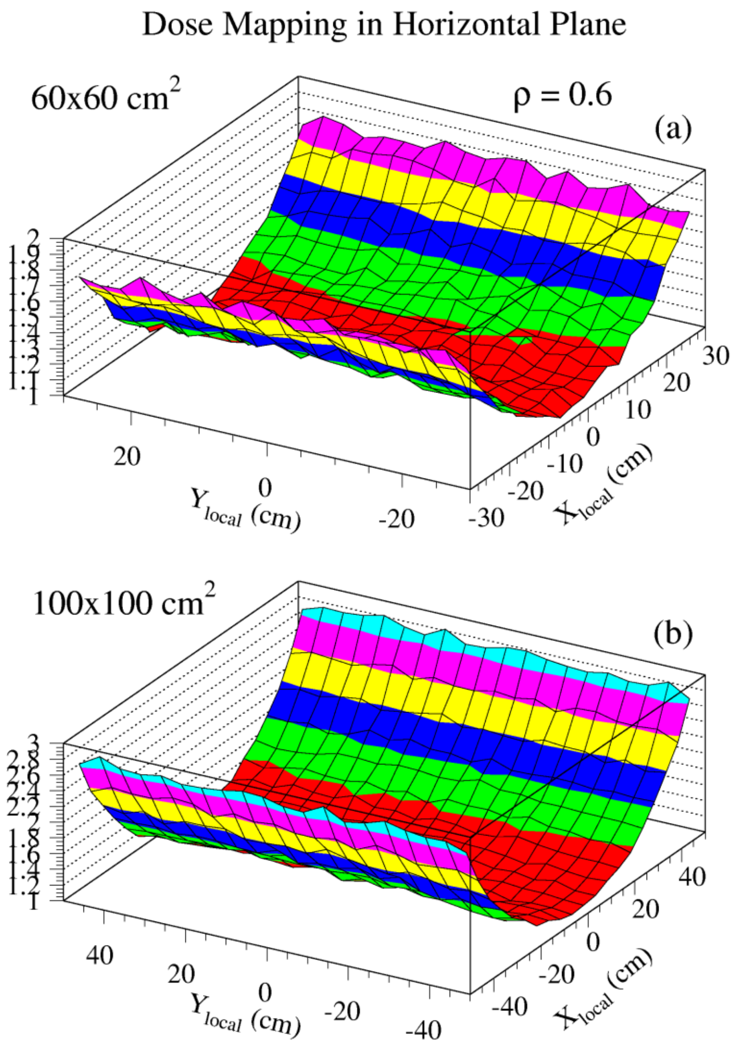
Penetration of High-Energy X-rays in Water



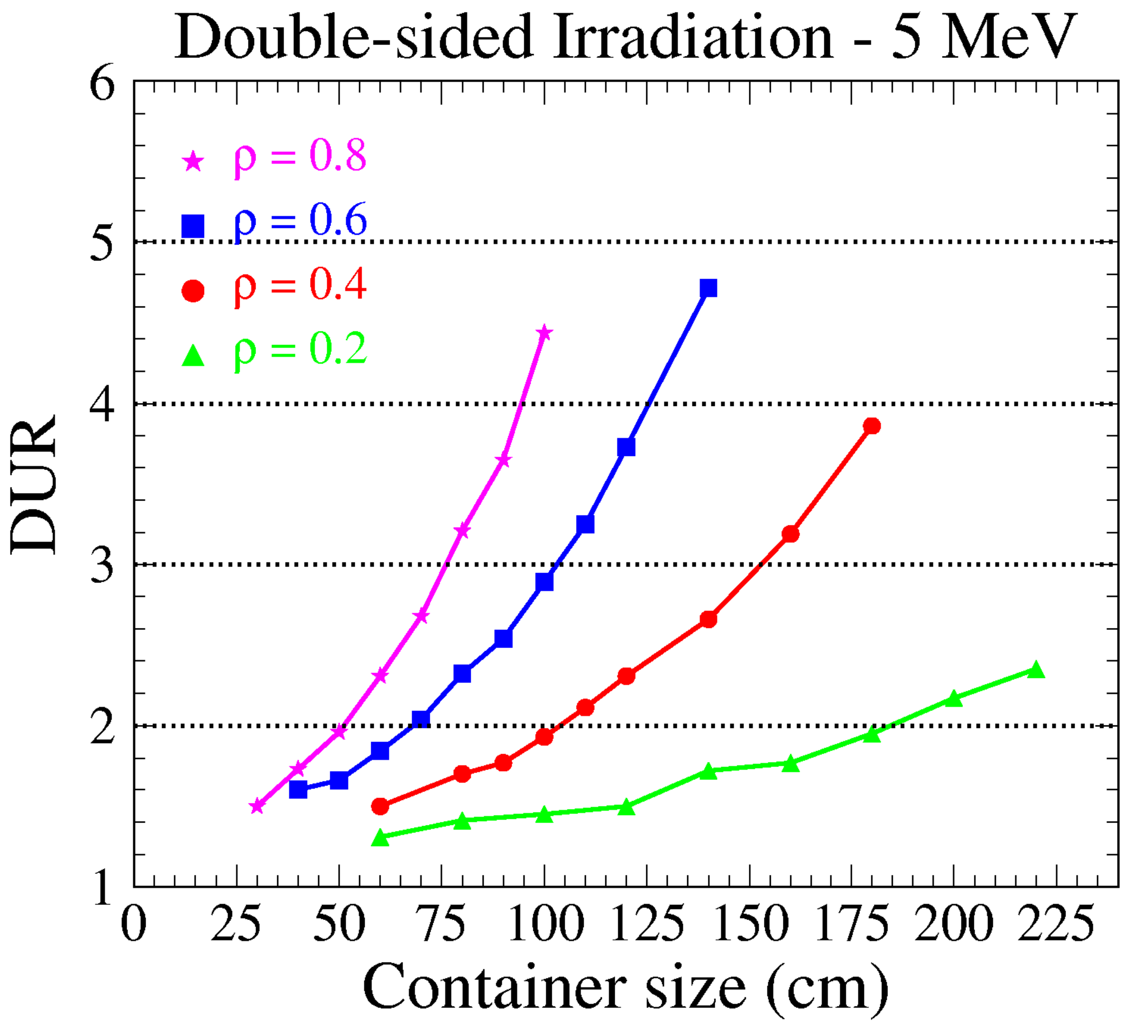
Optimum Thickness for Two-Sided Processing



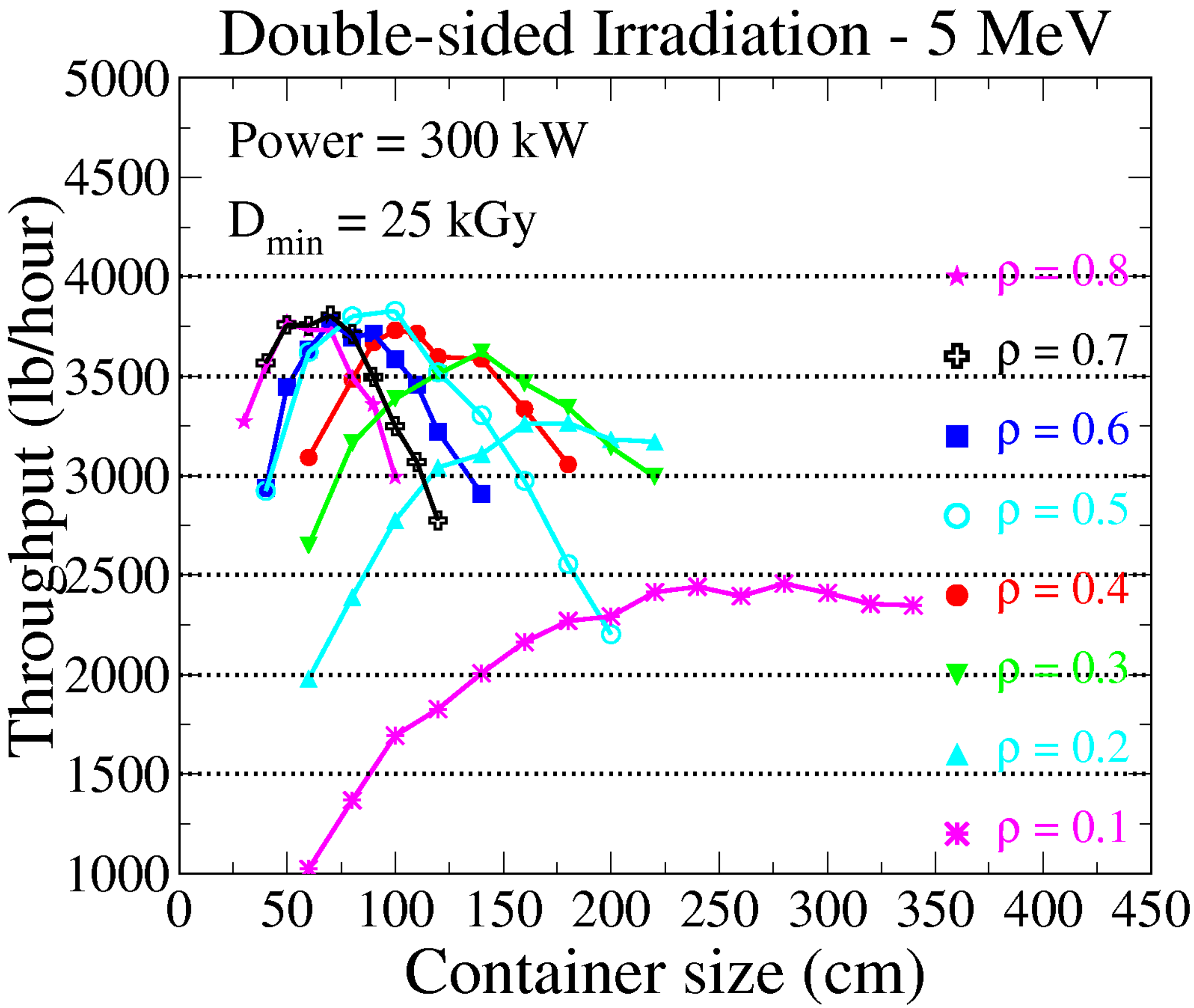
X-ray Dose vs Depth – Two Sided Process



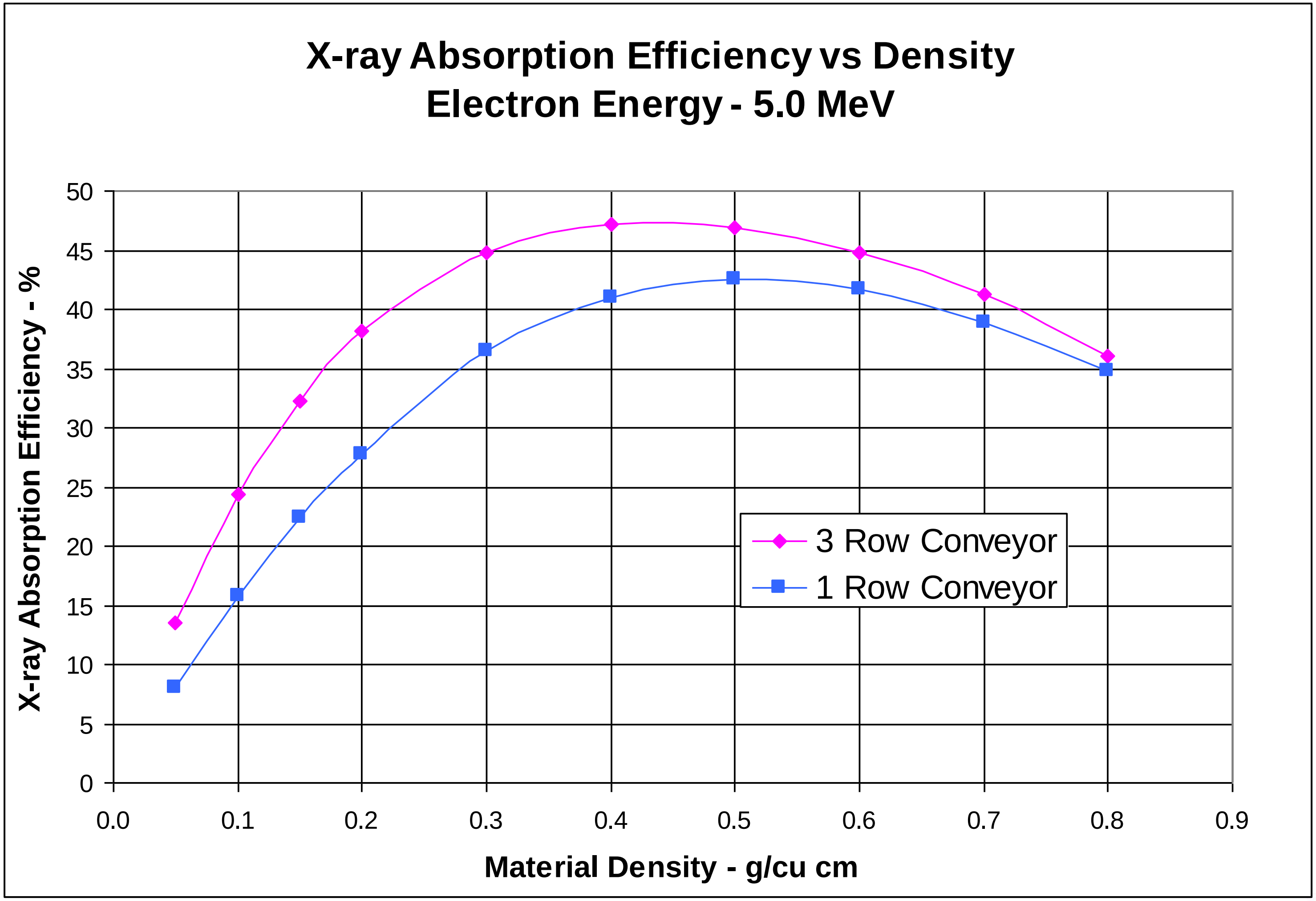
Dose Uniformity Ratio vs Depth and Density



Throughput Rate vs Depth and Density



X-ray Absorption Efficiency – Two Sided Process



Two-Sided X-ray Processing Data

Electron Energy (MeV)	X-Ray Efficiency (%)	Tenth Value Layer Calculation (cm water)	Optimum Thickness Double Sided (cm)	Max/Min Ratio
10.0	16.2	49.0	43	1.54
7.5	13.3	44.3	38	1.54
5.0	8.2	39.0	34	1.54
Co-60		31.0	28	1.75

Economic Comparisons, X-rays vs Gamma Rays

Capital Cost Comparison

The electron beam power available from a Dynamitron direct-current accelerator is now 300 kW at 5.0 MeV.

The forward X-ray power with 8% power conversion efficiency is 24 kW. This is nearly equivalent to the gamma-ray power emitted in all directions from 2.0 MCi of cobalt-60 sources.

With the recent price of $2.50 per curie, the initial cost of this much cobalt-60 is about $5.0 million US. This is slightly more than the price of a Dynamitron equipped with a high-power X-ray target and cooling system.

Economic Comparisons, X-rays vs Gamma Rays

Operating Cost Comparison

The annual cost of electrical power for a 300 kW, 5.0 MeV Dynamitron: 600 kW at $0.12 per kW-hr for 8000 hours per year is about $576,000.

The annual cost of source replenishment for radioactive decay of cobalt-60: 12.3% per year of 2.0 MCi at $2.50 per curie is about $615,000.

Operating costs for management, labor and maintenance are probably about the same for continuous operation with either an X-ray or a gamma-ray facility of this size.

Economic Comparisons, X-rays vs Gamma Rays

Capital Cost Comparison

The electron beam power available from a Rhodotron radio-frequency accelerator is now 700 kW at 7.0 MeV.

The forward X-ray power with 11% power conversion efficiency is 77 kW. This is nearly equivalent to the gamma-ray power emitted in all directions from 6.0 MCi of cobalt-60 sources.

With the recent price of $2.50 per curie, the initial cost of this much cobalt-60 is about $15 million US. This is much more than the price of a Rhodotron equipped with a high-power X-ray target and cooling system.

Economic Comparisons, X-rays vs Gamma Rays

Operating Cost Comparison

The annual cost of electrical power for a 700 kW, 7.0 MeV Rhodotron: 1400 kW at $0.12 per kW-hr for 8000 hours per year is about $1.34 million US.

The annual cost of source replenishment for radioactive decay of cobalt-60: 12.3% per year of 6.0 MCi at $2.50 per curie is about $1.85 million US.

Operating costs for management, labor and maintenance are probably about the same for continuous operation with either an X-ray or a gamma-ray facility of this size.

Economic Comparisons, X-rays vs Gamma Rays

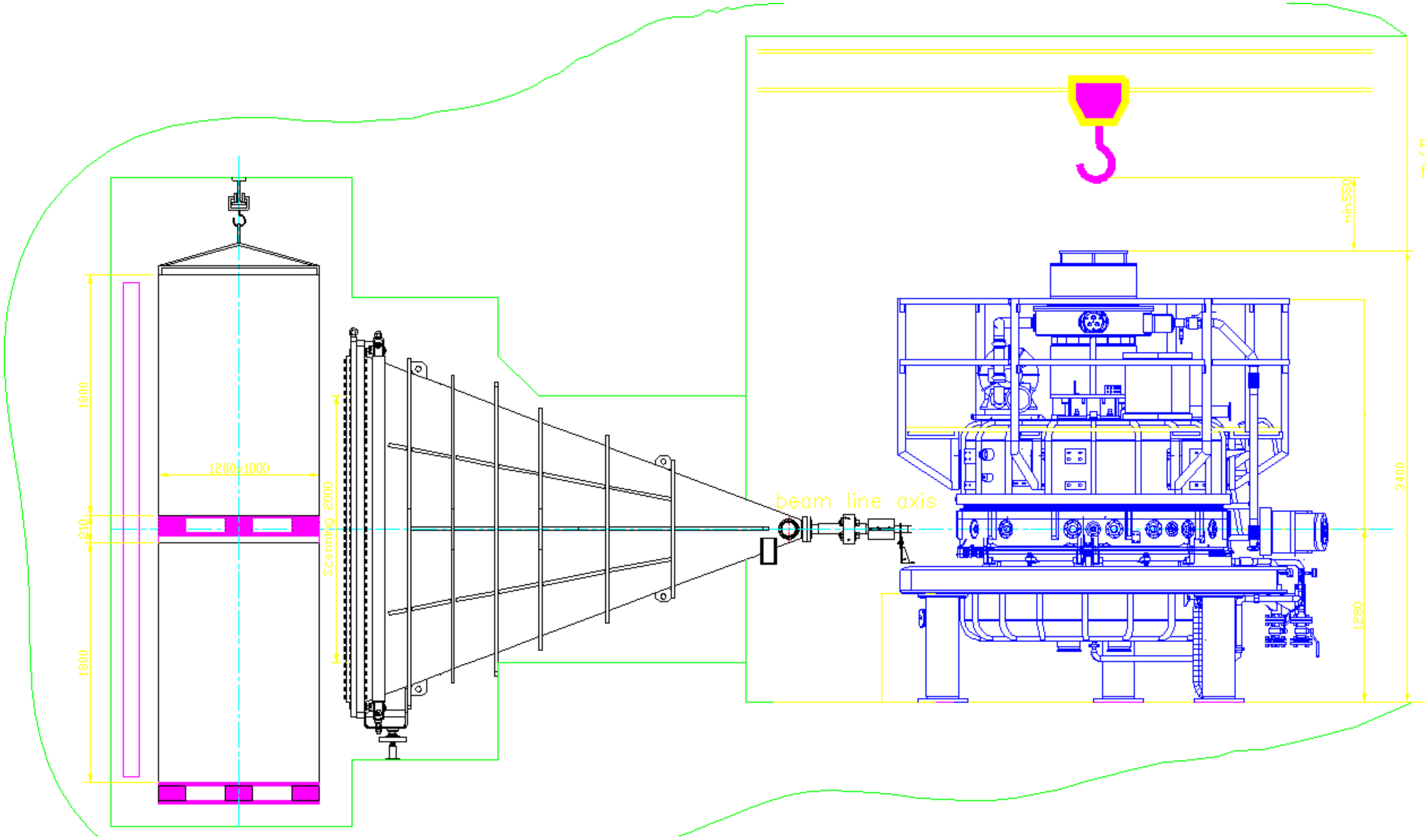
If the work load in an irradiation facility does not need continuous operation, then an accelerator can be turned off when it is not needed and the annual cost for electric power and labor can be reduced.

On the other hand, a radioactive source is always on. So, the facility usually requires operating personnel for 24 hours per day.

The source loading in an irradiation service center might need to be somewhat higher than the average annual requirement to take care of fluctuations in the work load.

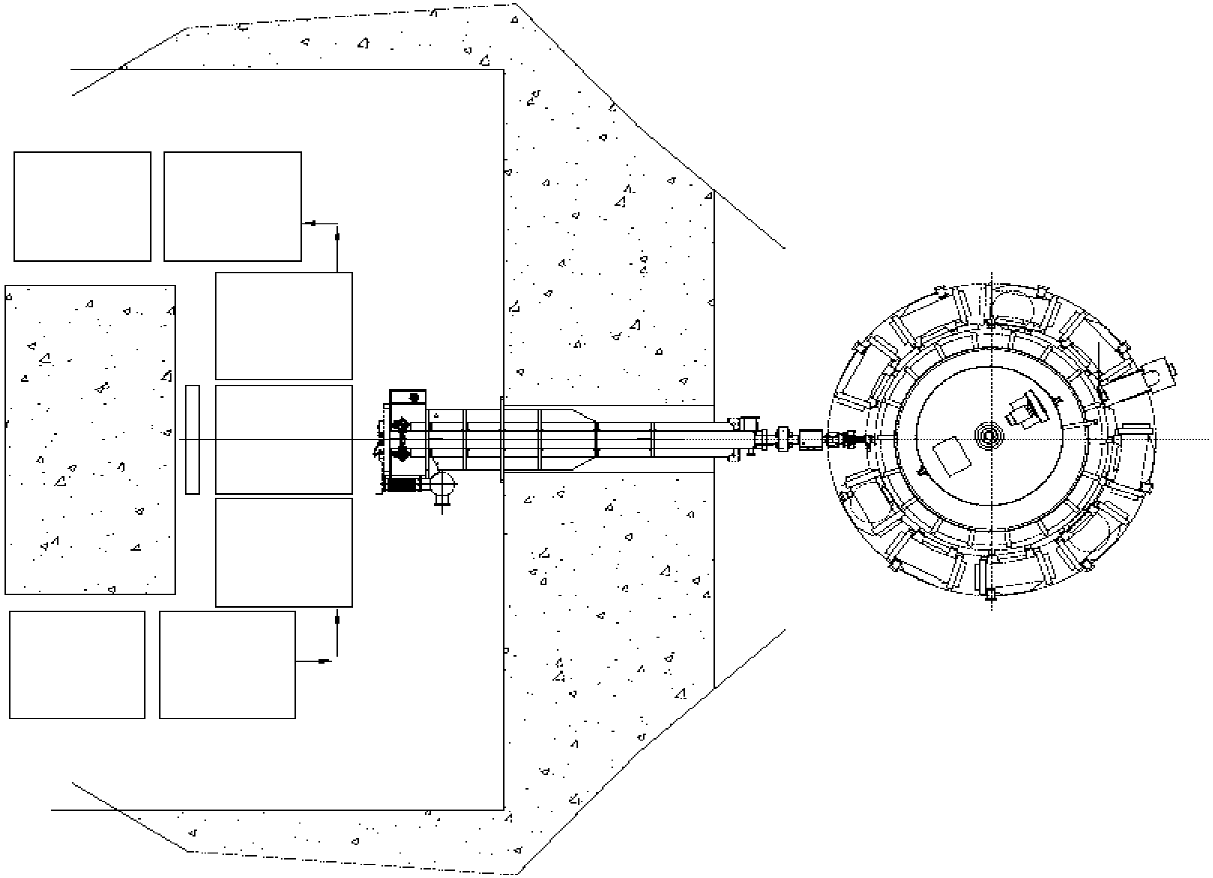
IBA eXelis® Four-Pass X-ray Process

Side View



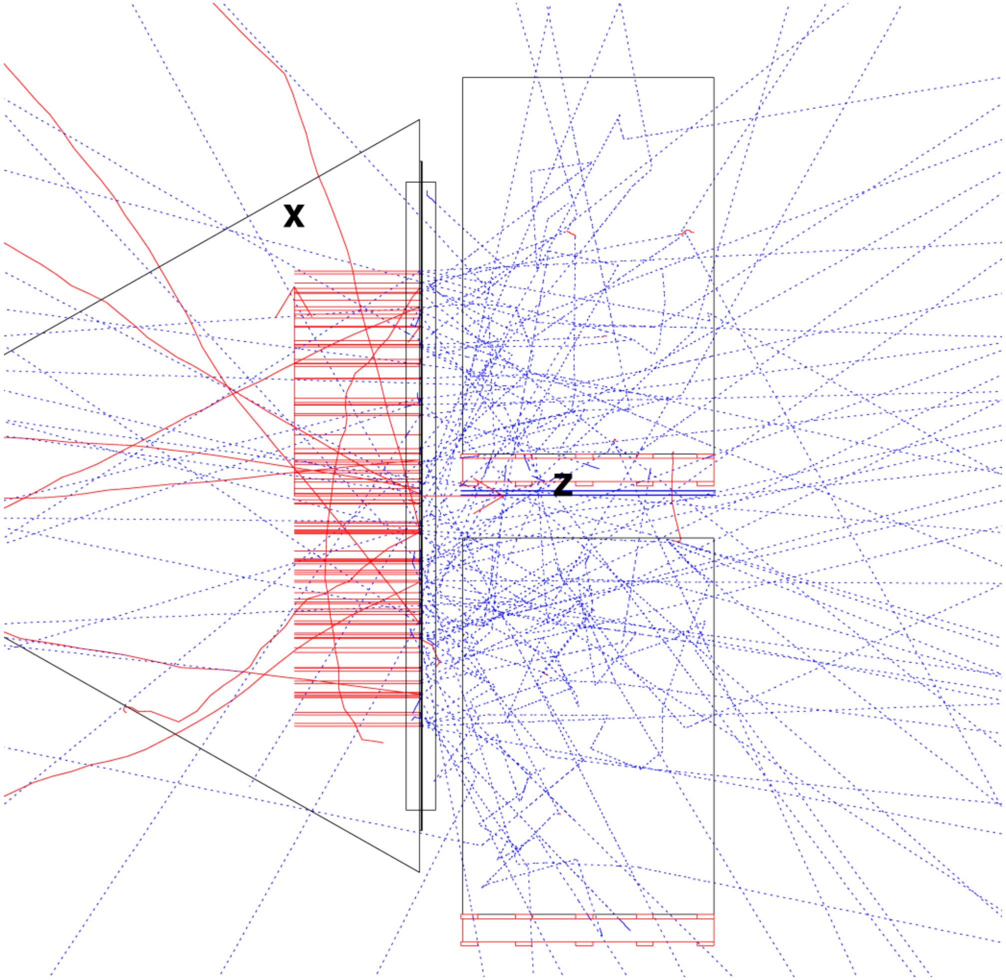
IBA eXelis® Four-Pass X-ray Process

Top View



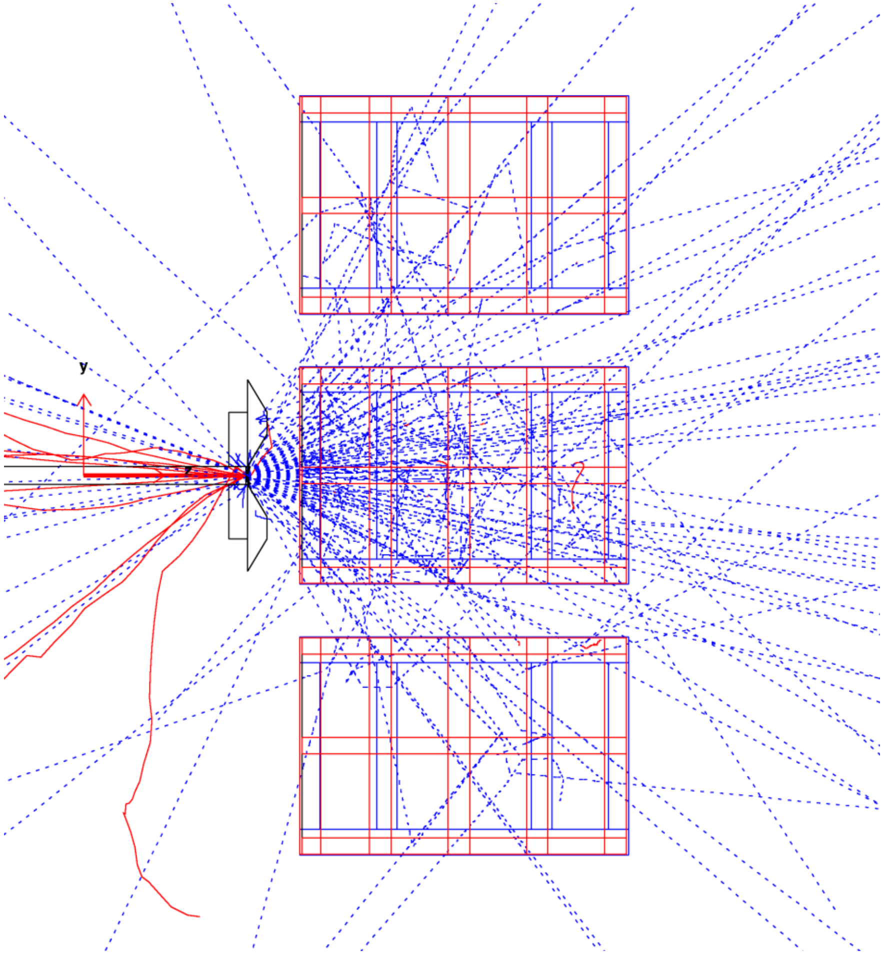
Monte Carlo Simulation of X-ray Paths

Side View

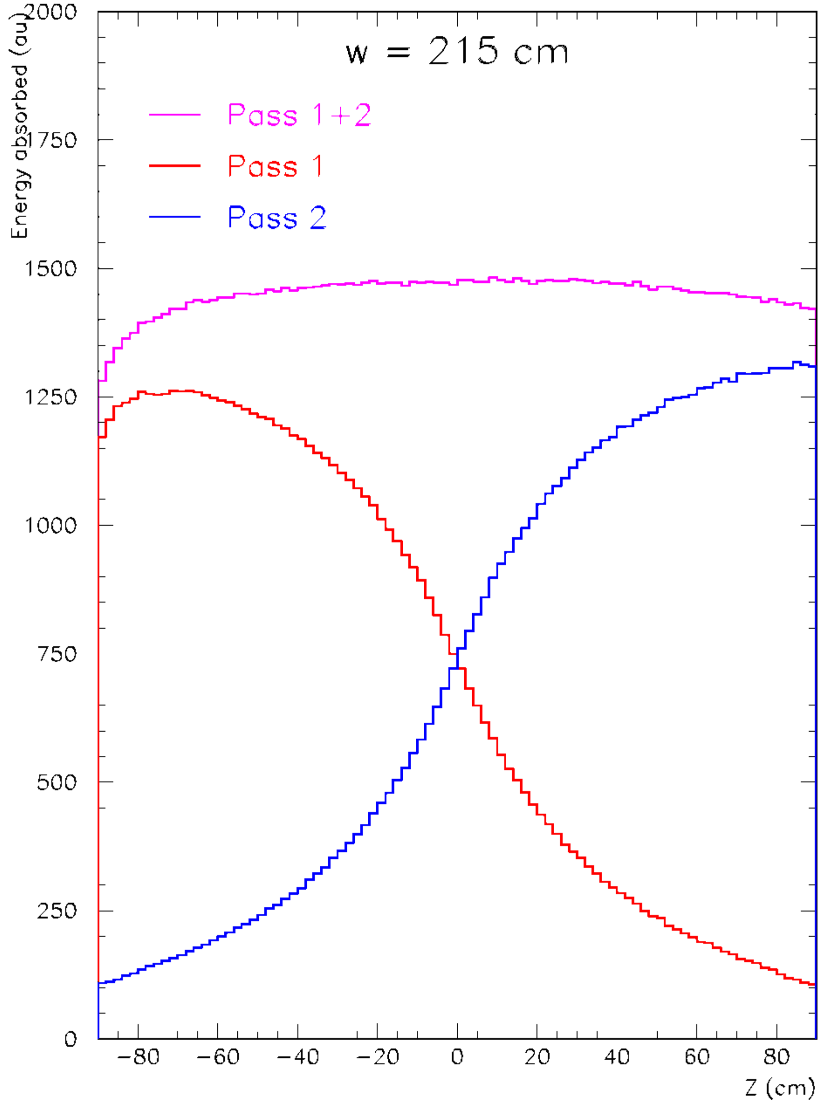


Monte Carlo Simulation of X-ray Paths

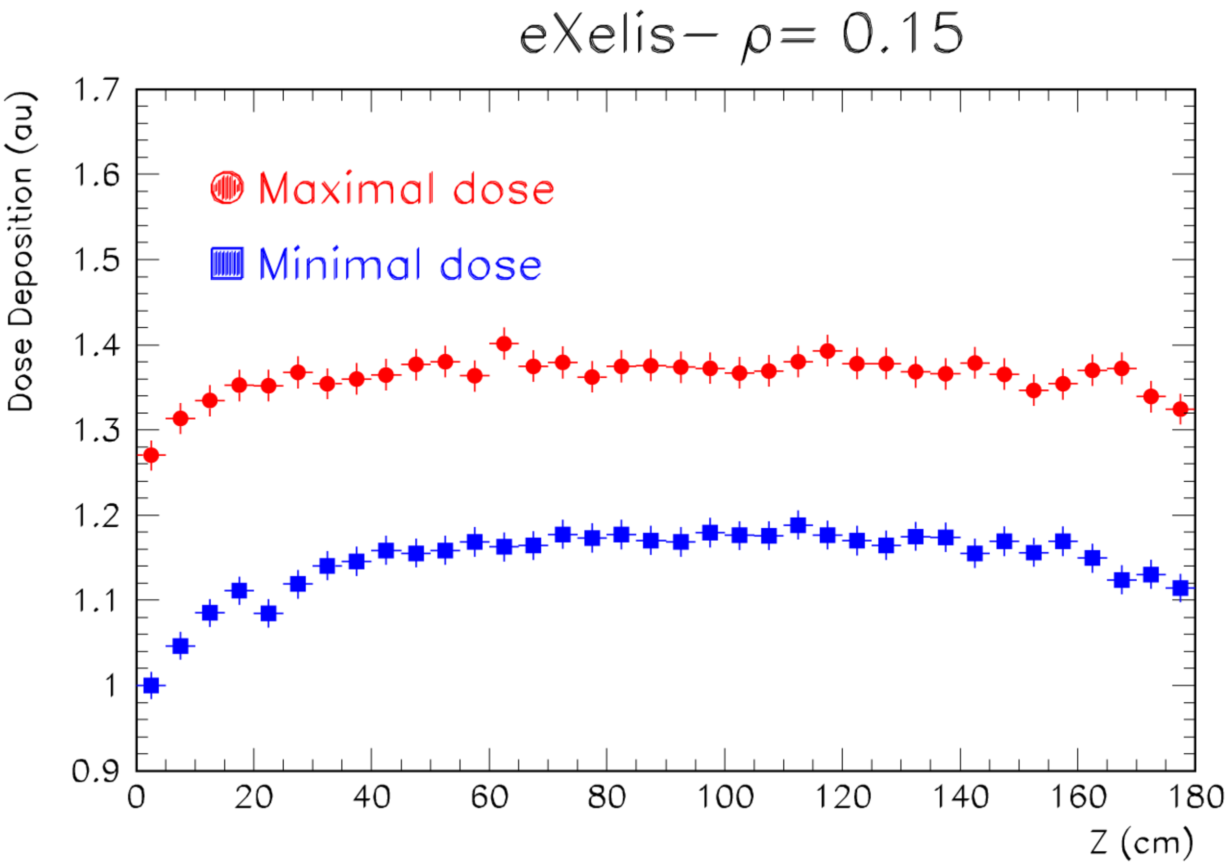
Top View



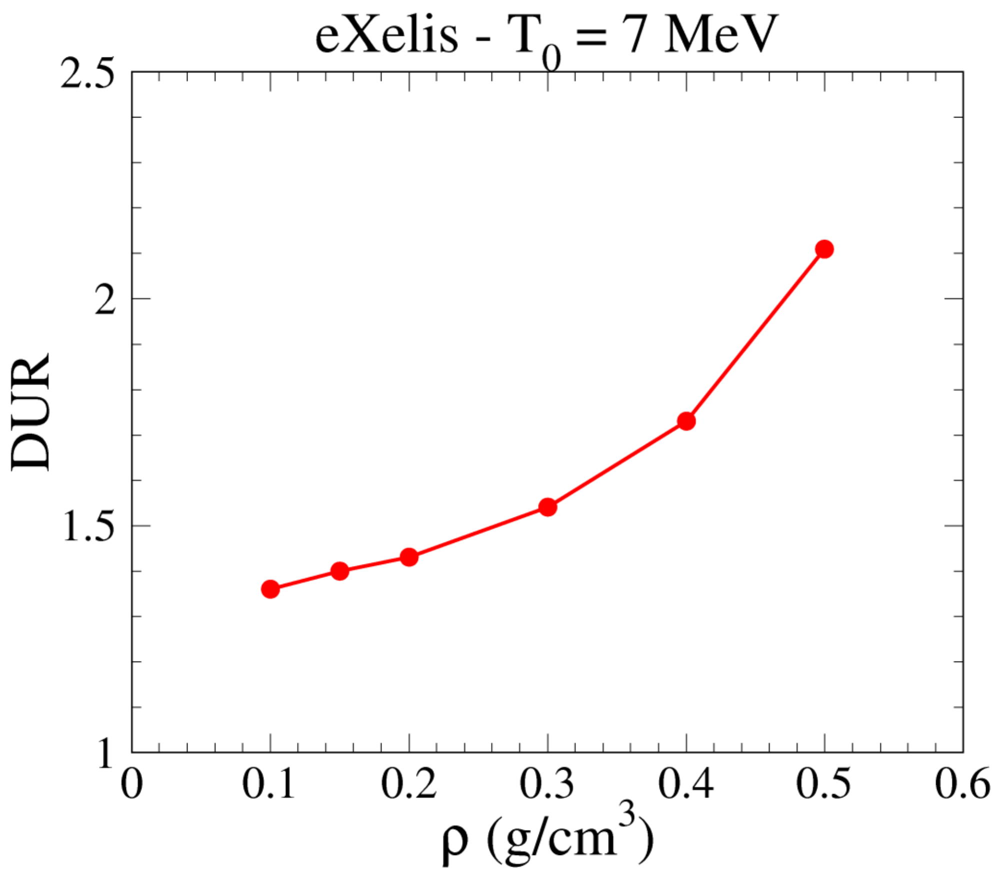
Vertical Dose Profiles – eXelis® Process



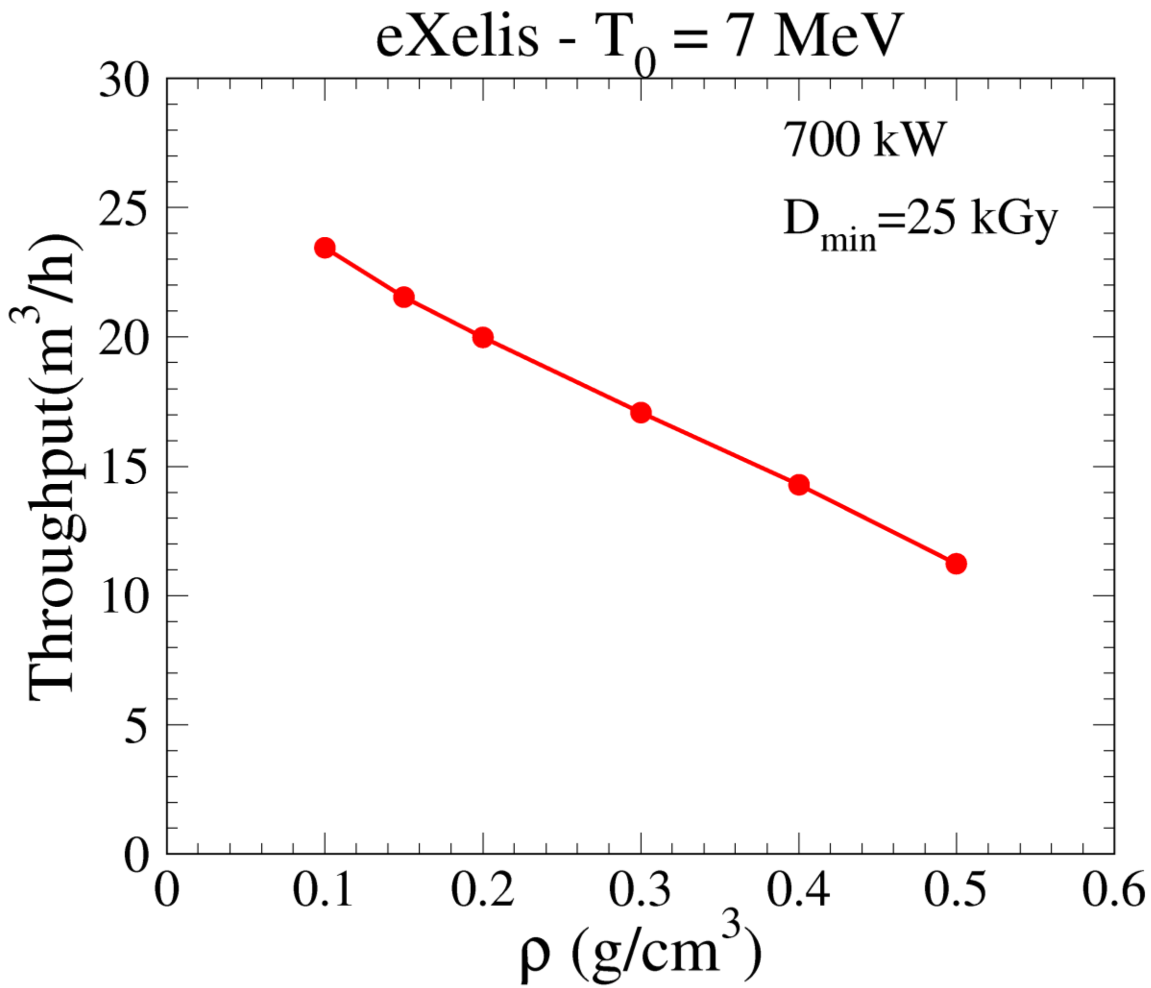
Vertical Dose Profiles – eXelis® Process



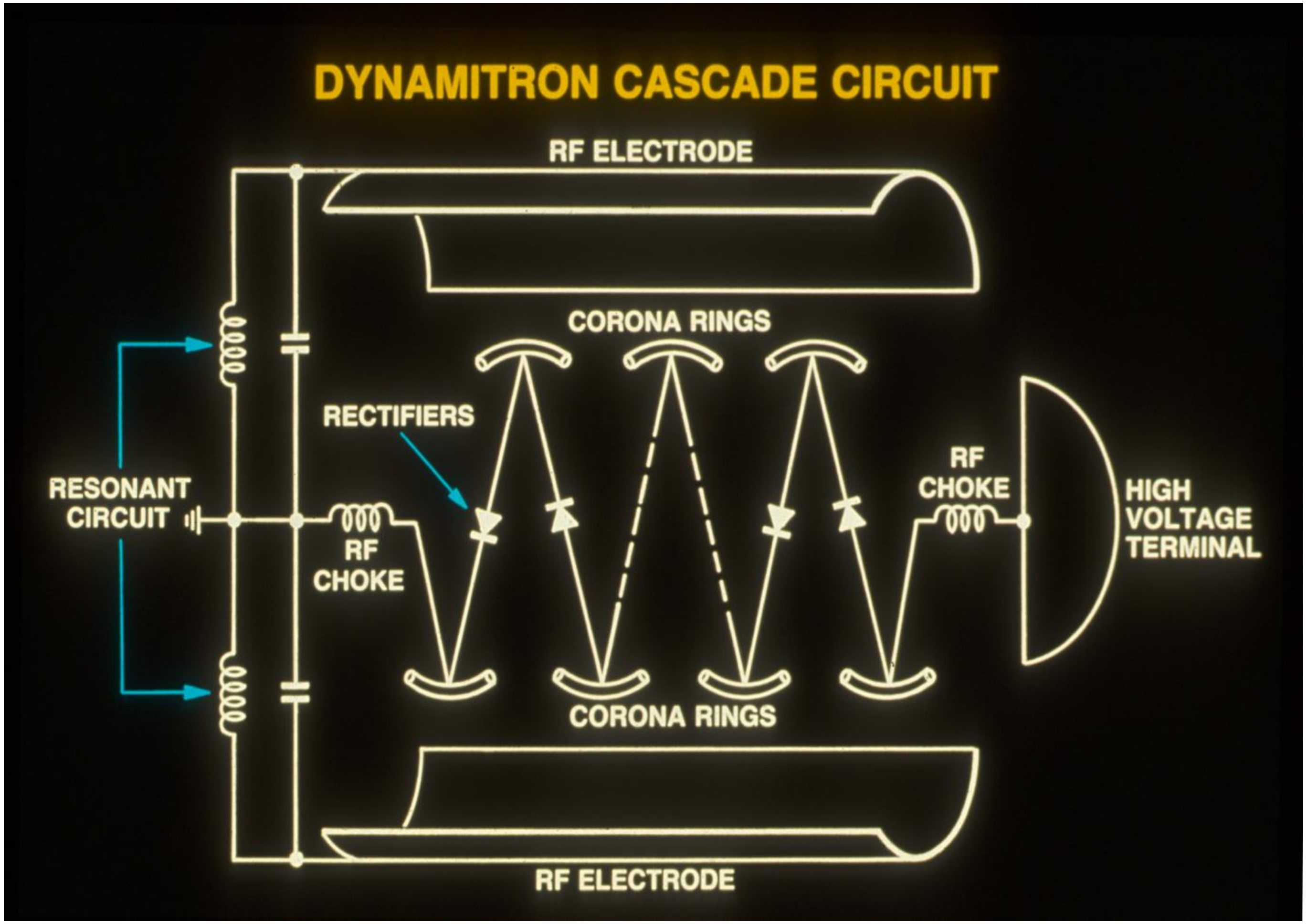
Dose Uniformity Ratios – eXelis® Process



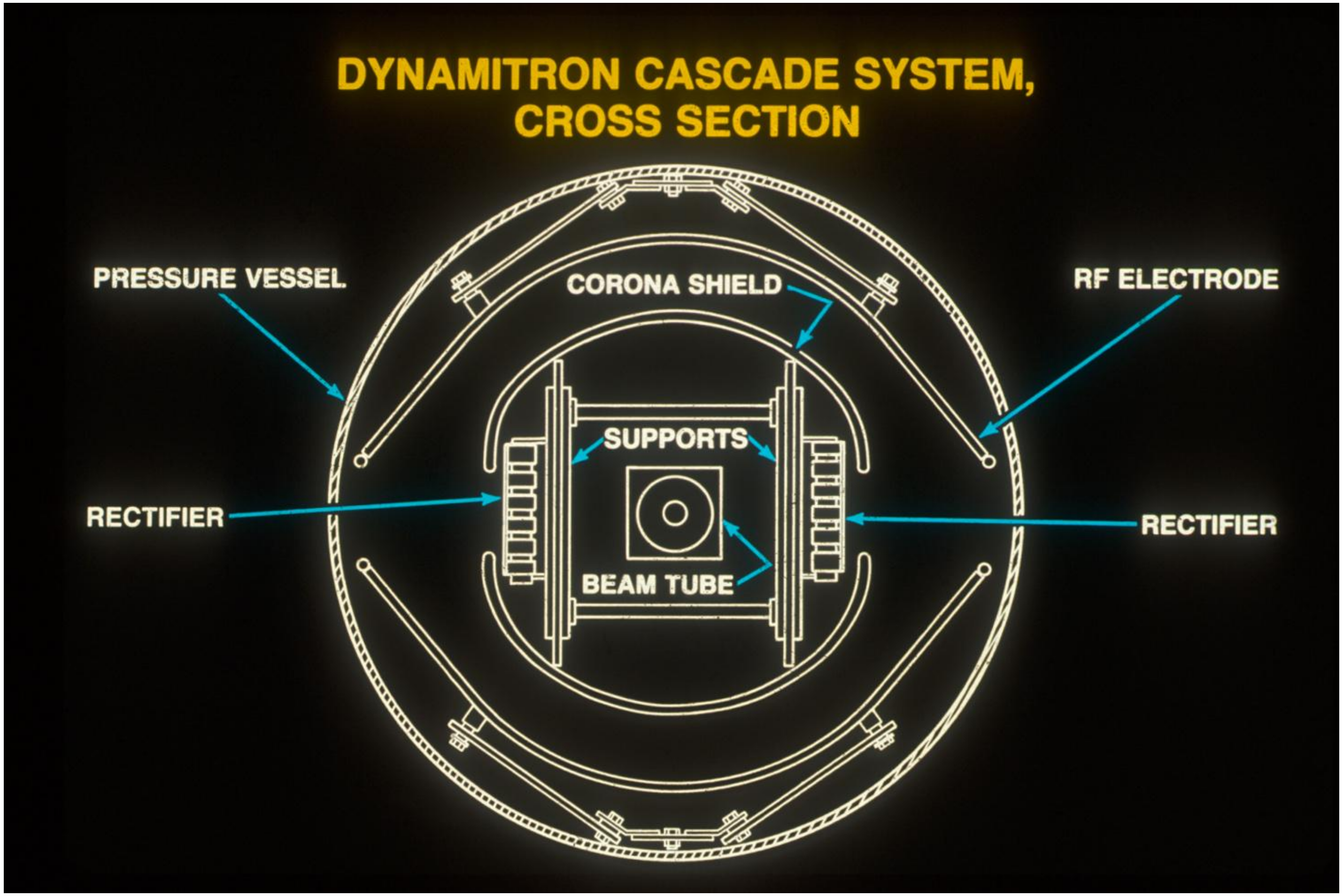
Throughput Rates - eXelis® Process



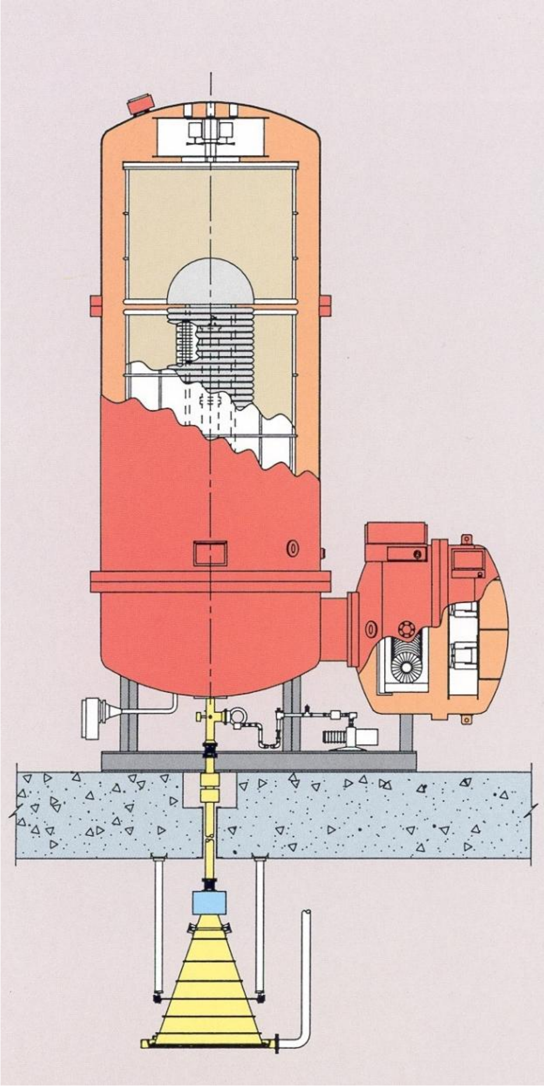
Dynamitron® High-Voltage Generator



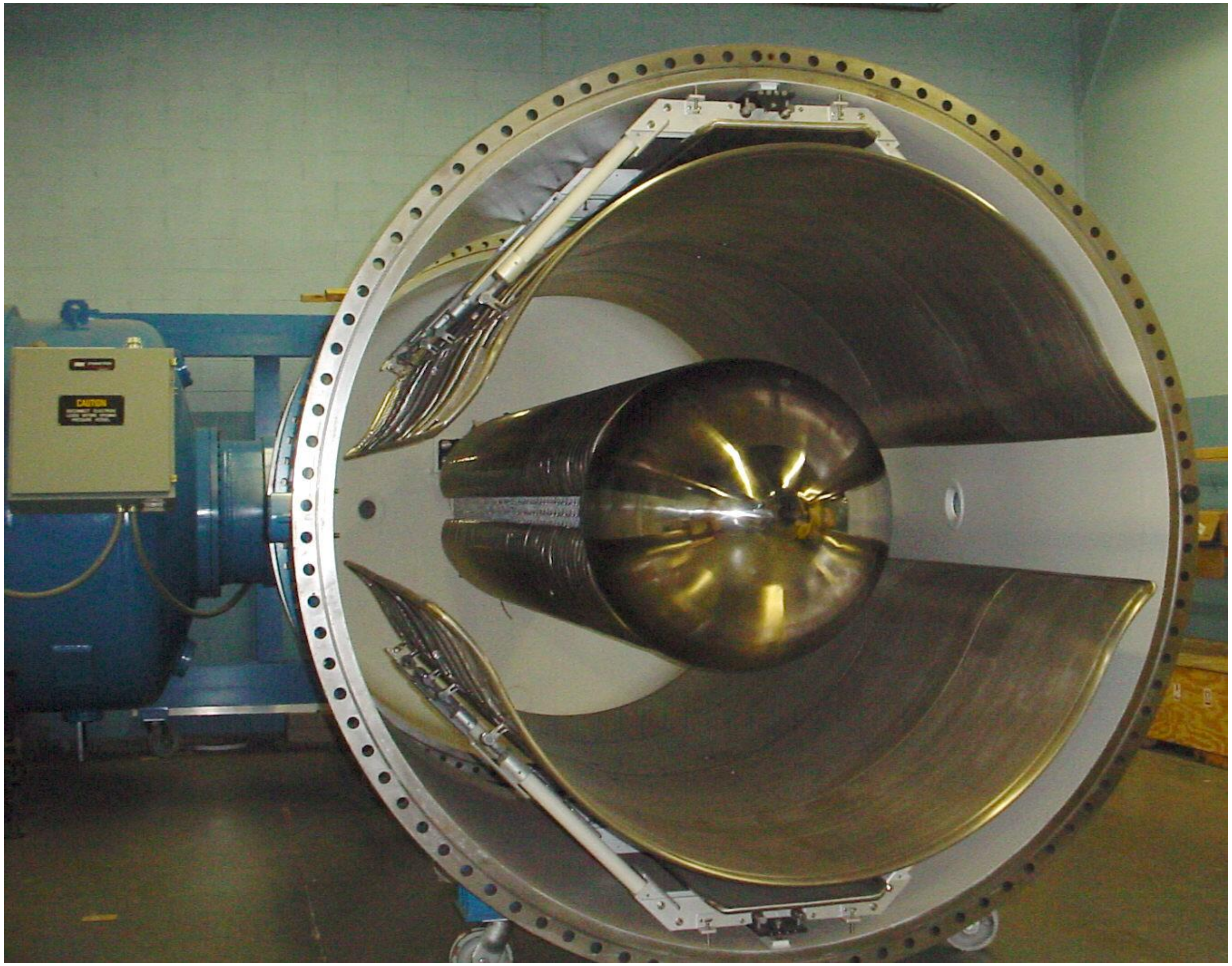
Dynamitron EB Accelerator Configuration



Dynamitron 5 MeV EB Accelerator System



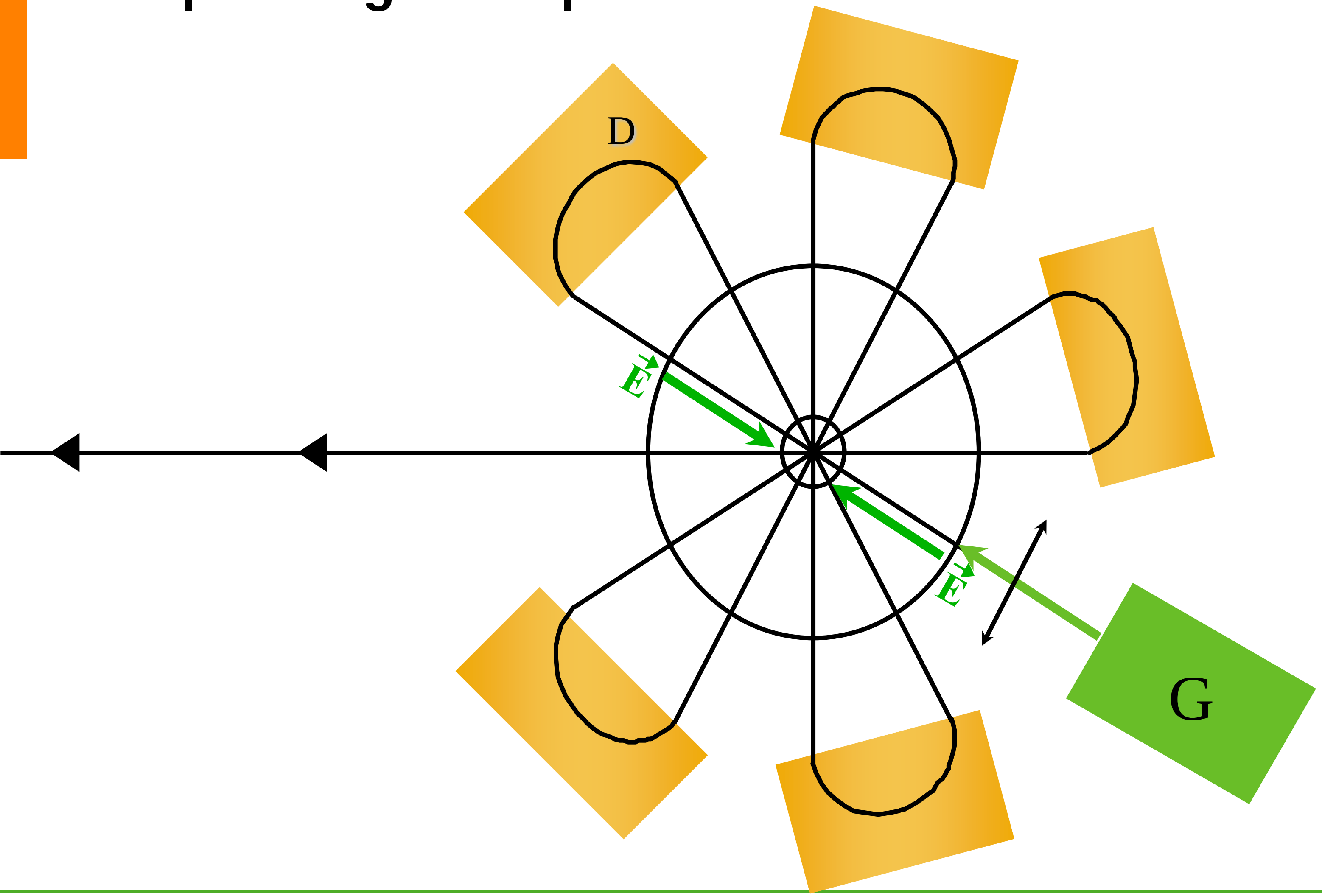
Dynamitron 5.0 MeV, 300 kW EB Accelerator



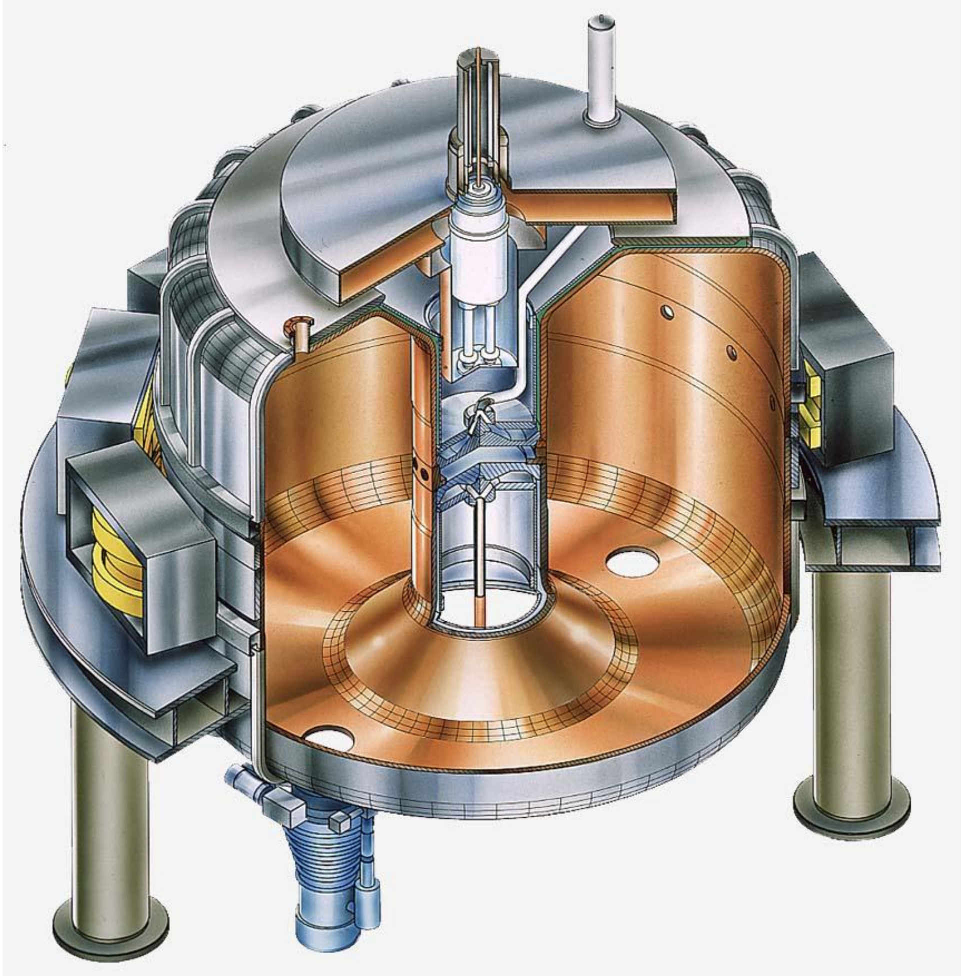
Dynamitron 5 MeV Pressure Vessel

Rhodotron® EB Accelerator Concept

Operating Principle

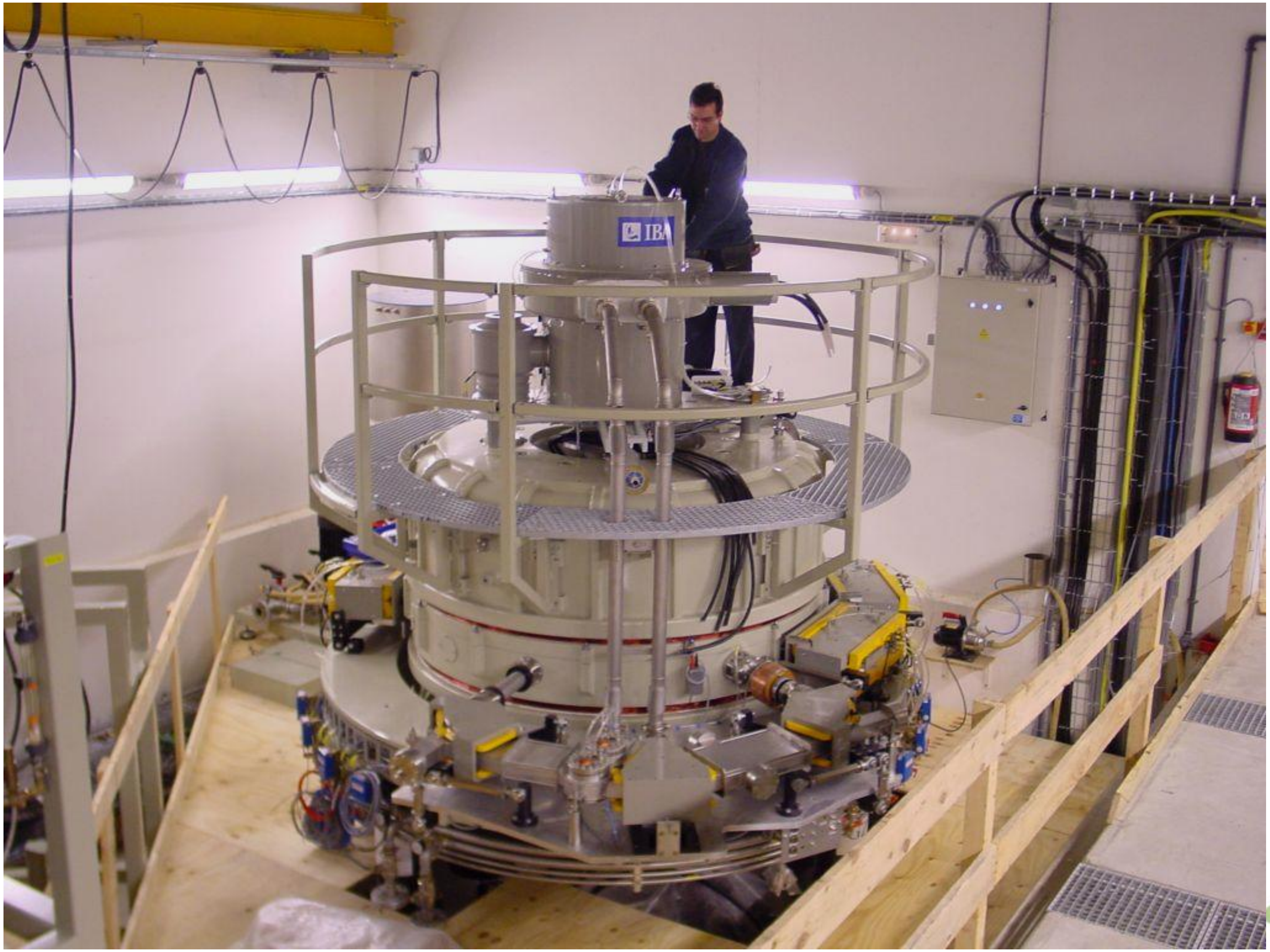


Rhodotron EB Accelerator Configuration



Rhodotron 10 MeV, 200 kW EB Accelerator

Rhodotron 7.0 MeV, 700 kW EB Accelerator



SHI EB and X-ray Facility in Tsukuba, Japan

SHI Dynamitron Facility – Tsukuba, Japan

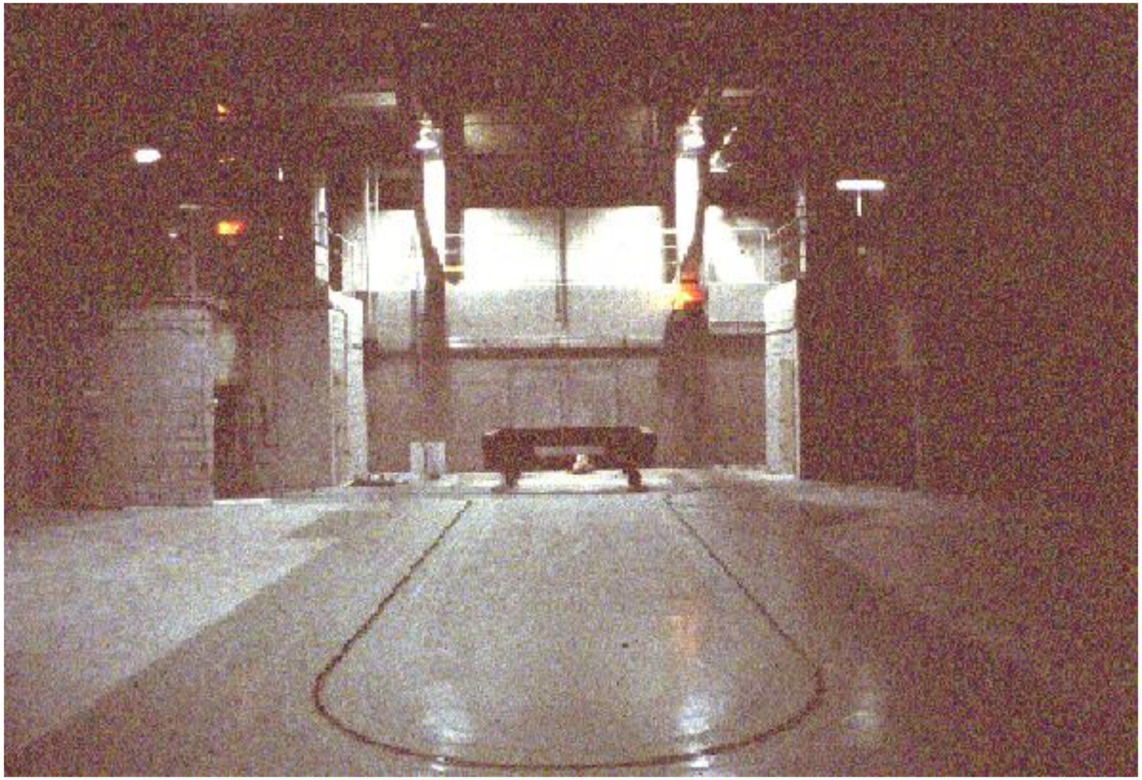
X-ray Product Conveyor Carts

SHI Dynamitron Facility – Tsukuba, Japan

Conveyor Cart Loading and Unloading Area

SHI Dynamitron Facility – Tsukuba, Japan

Conveyor Cart Loading and Unloading Area



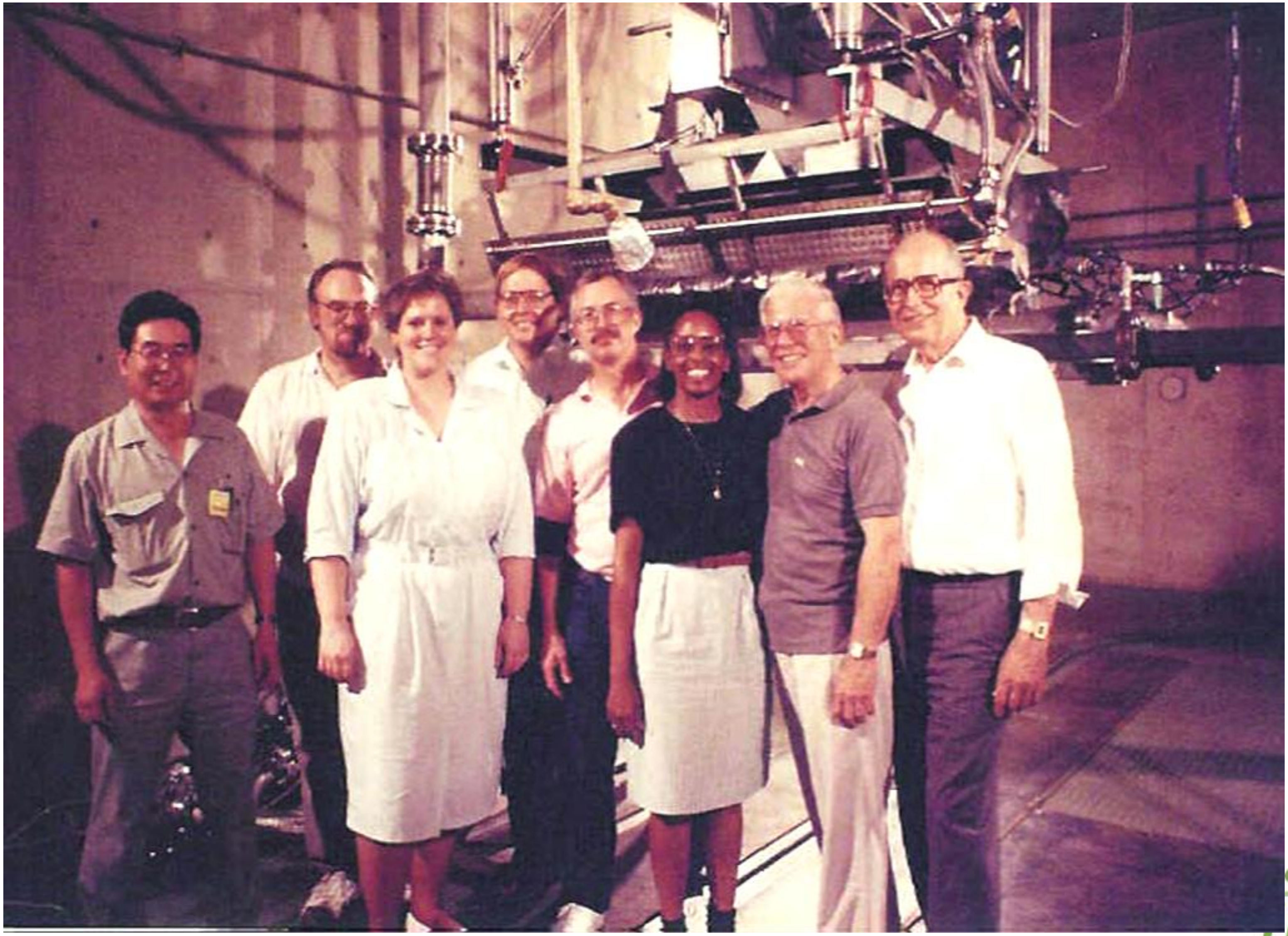
SHI Dynamitron Facility – Tsukuba, Japan

Tantalum X-ray Target for 300 kW EB Power

SHI Dynamitron Facility – Tsukuba, Japan

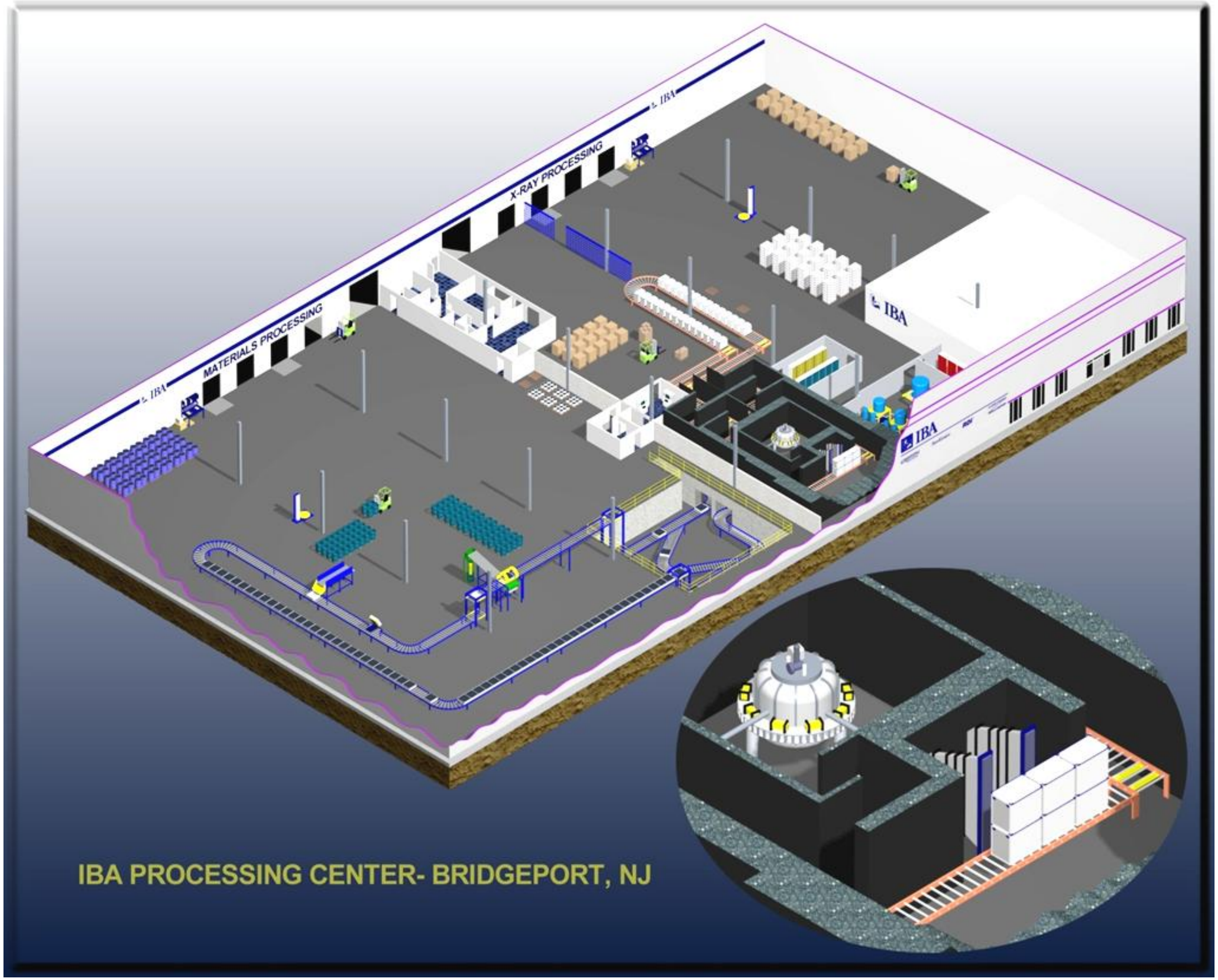
X-ray Target Cooling System for 300 kW EB Power

X-ray Target Evaluation Team in SHI Facility



EB and X-ray Rhodotron Facility in Bridgeport, NJ

EB and X-ray Rhodotron Facility in Bridgeport, NJ



EB and X-ray Rhodotron Facility in Bridgeport, NJ

Vertical Scanning Horn for Electron Beam Processing

EB and X-ray Rhodotron Facility in Bridgeport, NJ

Thin Packages for Electron Beam Processing

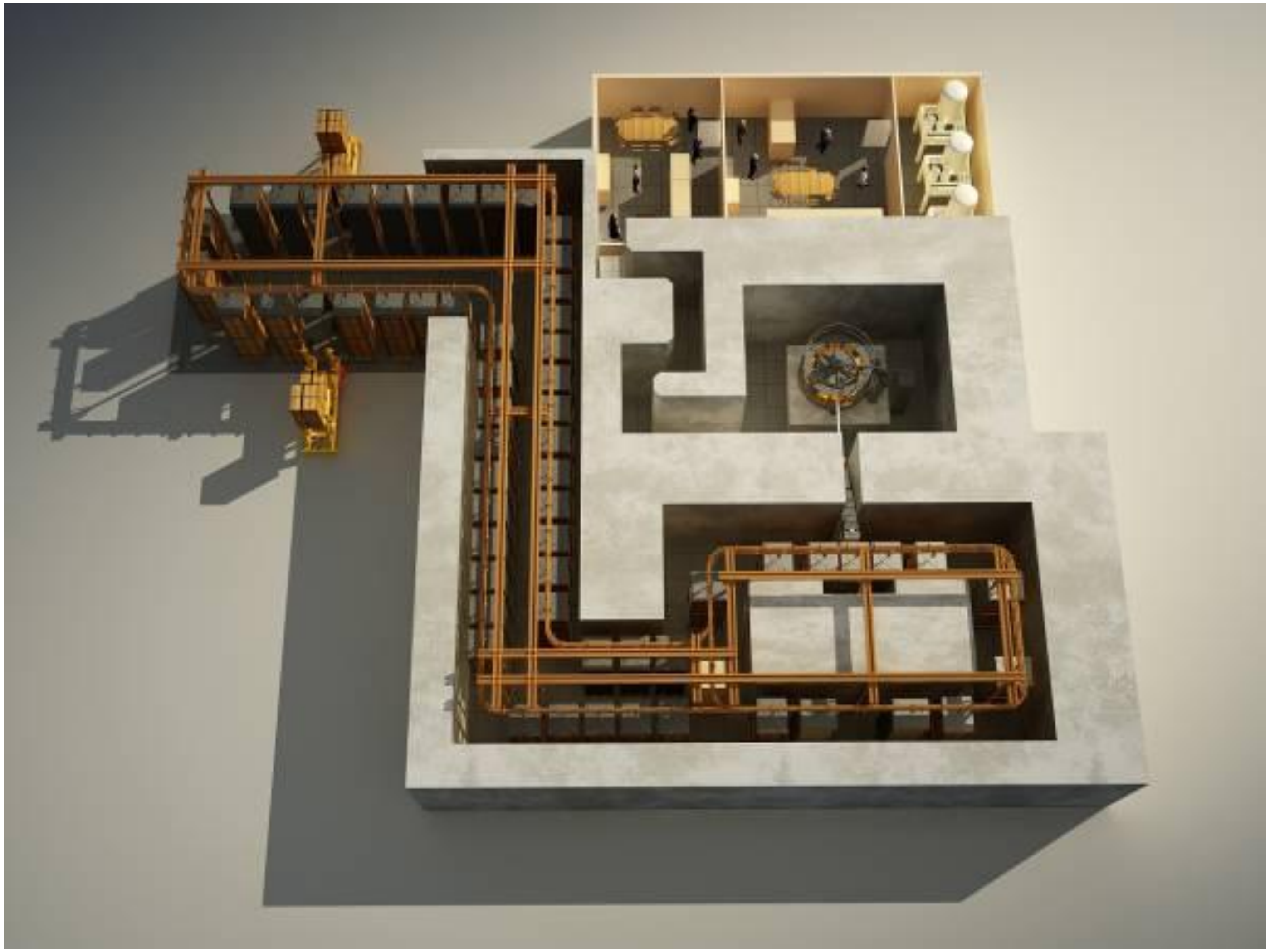
EB and X-ray Rhodotron Facility in Bridgeport, NJ

X-ray Product Tote Loading and Unloading Area

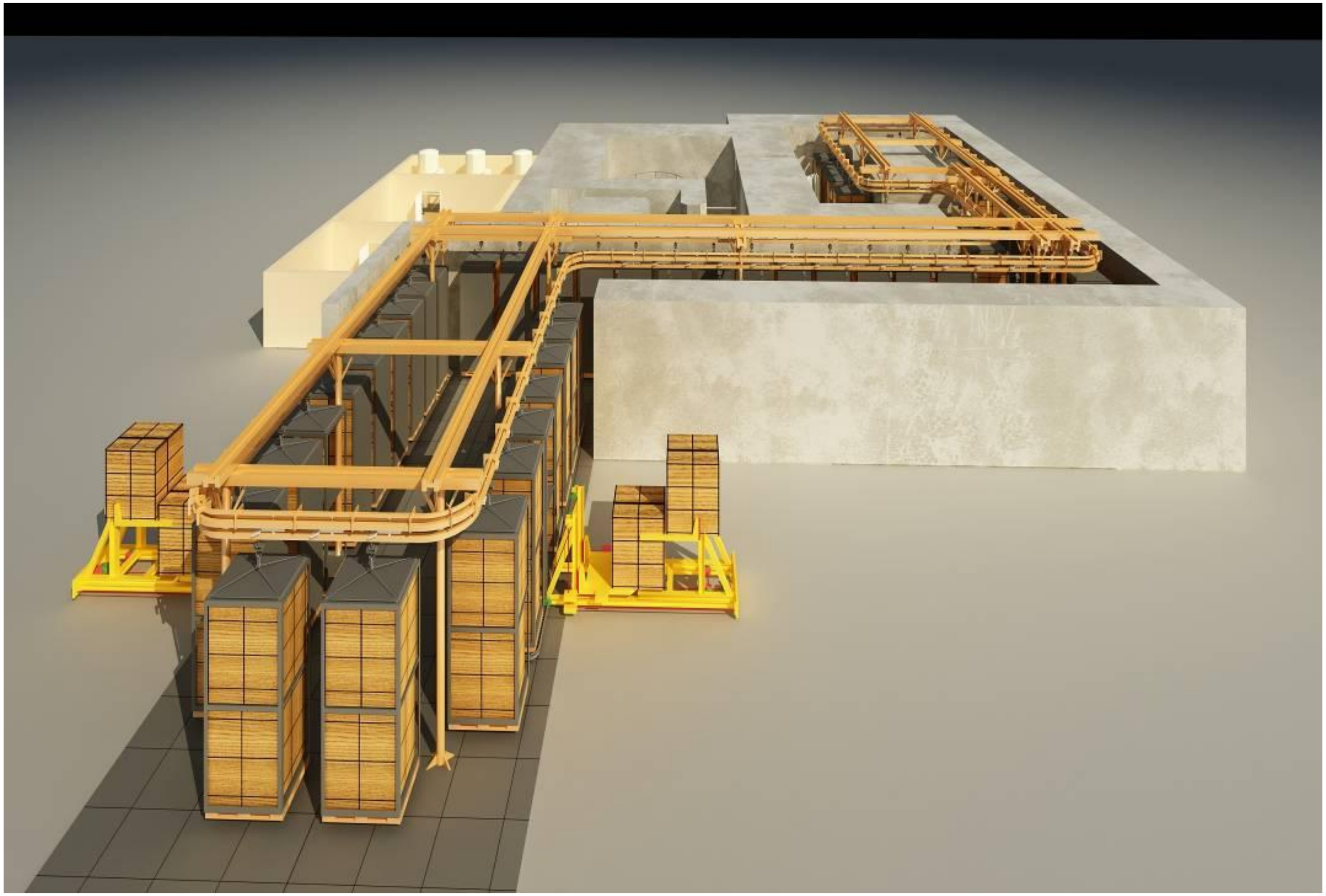
EB and X-ray Rhodotron Facility in Bridgeport, NJ

Dual Tote Carriers Approaching the X-ray Targets

LEONI Studer Hard X-ray Facility in Switzerland



LEONI Studer Hard X-ray Facility in Switzerland



Leoni Studer Hard X-Ray Facility

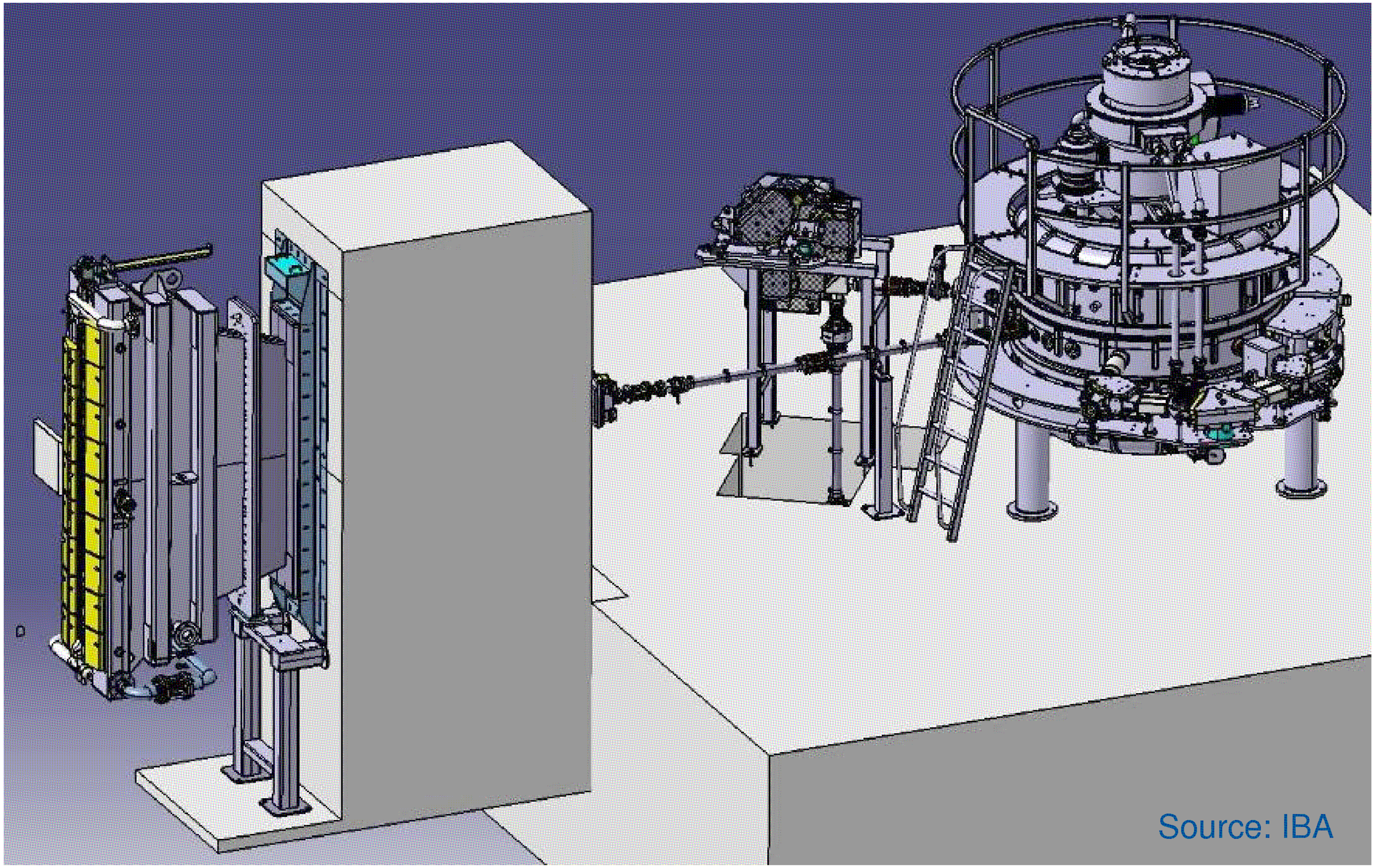
- First X-ray facility based upon the TT1000 Rhodotron installed at Leoni Studer Hard in Däniken (Switzerland)
- 7 MeV/ 700 kW electron beam used to produce X-ray for medical devices sterilization.

- Location: Däniken (CH)
- Founded 1984
- Around 95 HC
- 7 accelerators (0.5 to 10 MeV)
- 1 ^{60}Co pallet unit
- 1 X-ray pallet unit

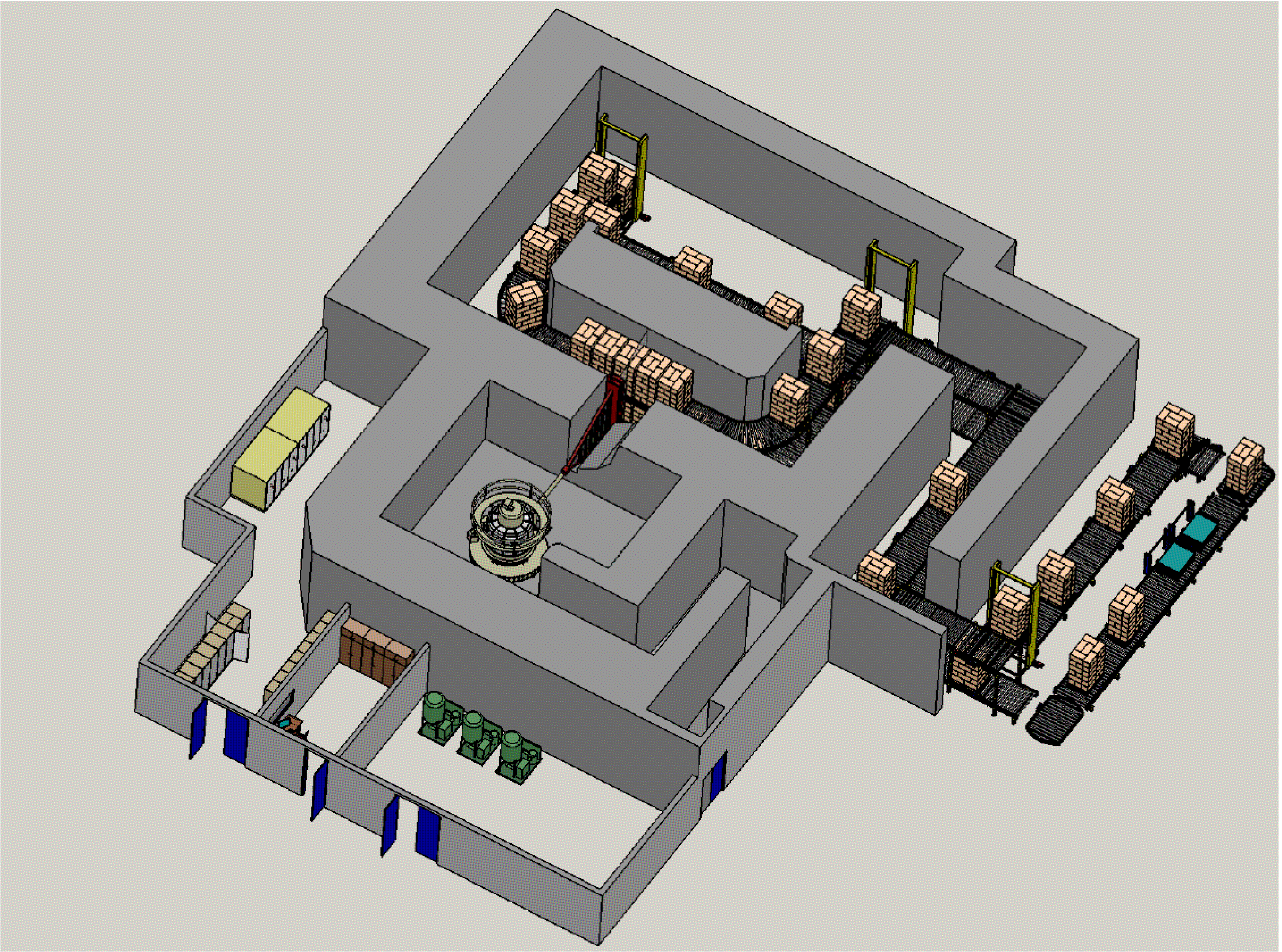
Leoni Studer Hard X-Ray Facility

2.6 m Scanning Horn

TT1000



Leoni Studer Hard X-Ray Facility



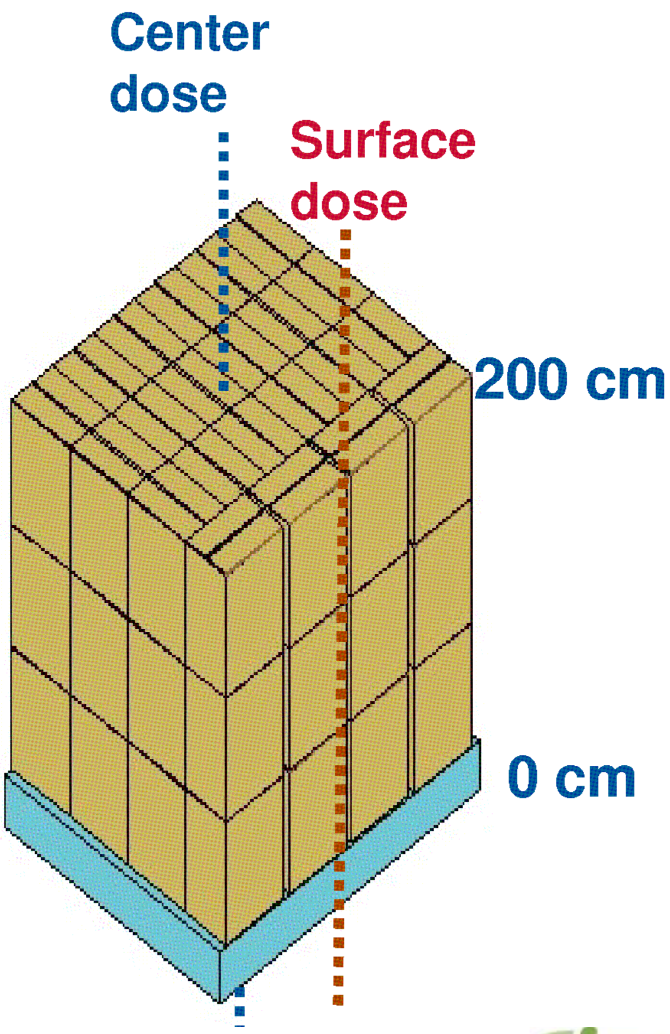
Leoni Studer Hard X-Ray Facility

- Two levels of 1.8 m high pallets to ensure vertical dose uniform
- Double-sided irradiation

➔ Each pallet passes 4 times in front of the X-ray converter

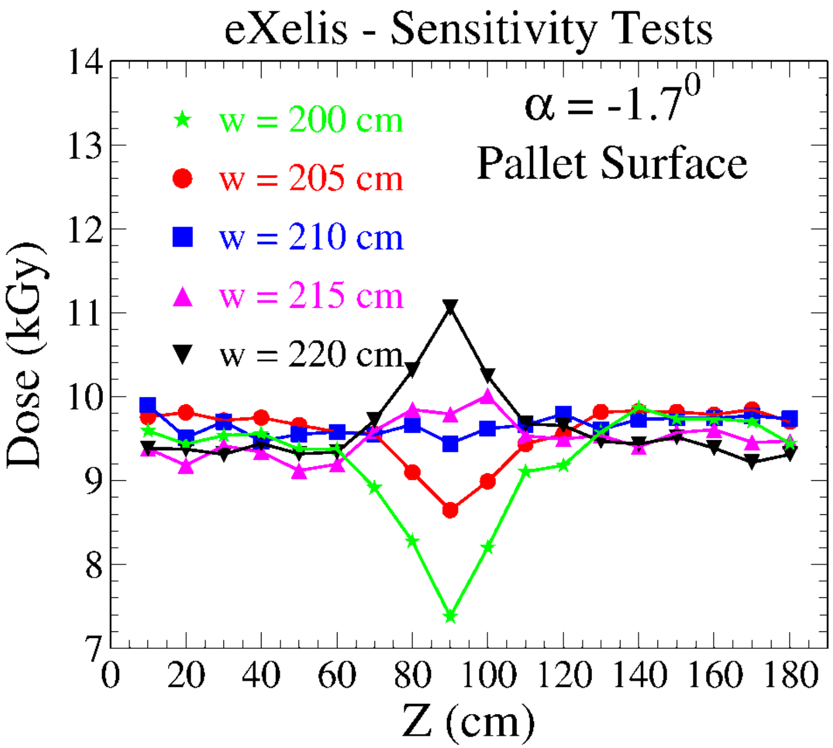
Leono Studer Hard Irradiation Tests

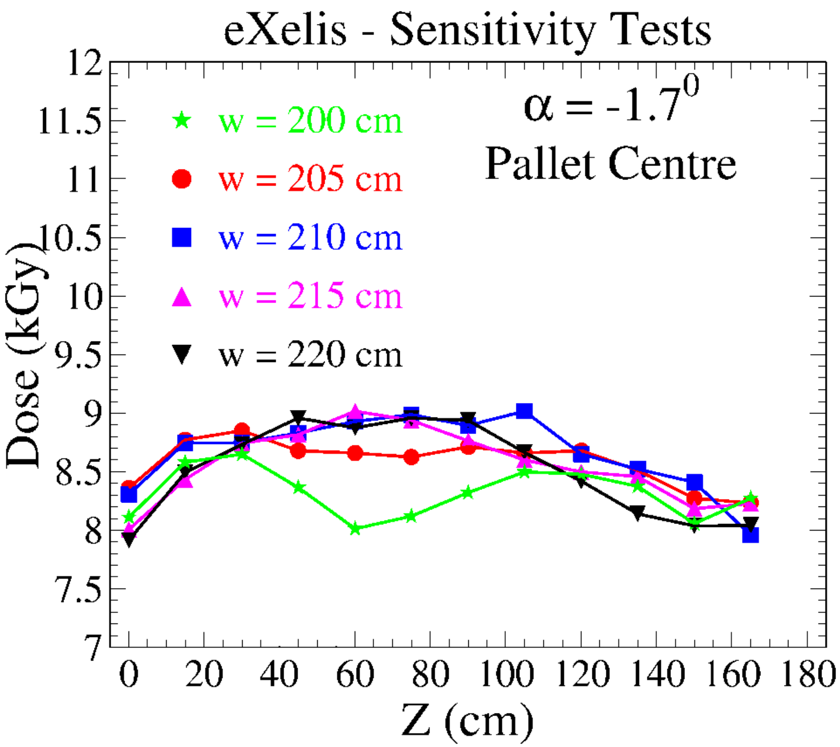
- First irradiation tests performed in Septembre / Octobre 2010.
- Full size pallet (100x120x180 cm^3) with density $\rho = 0.15\ g/cm^3$ loaded with Alanine pellets.
- Dosimeters placed every 10 or 15 cm along vertical axis, in the pallet center and at the surface.
- Optimization of:
  - Beam parallelism (convergence angle α)
  - Scanning width w



Leoni Studer Hard Test Results

Evolution of dose along vertical axis for α = -1.7°





w is too short (200 cm) ➔ hole at the pallet mid-height
w is too large (220 cm) ➔ peak at the pallet mid-height

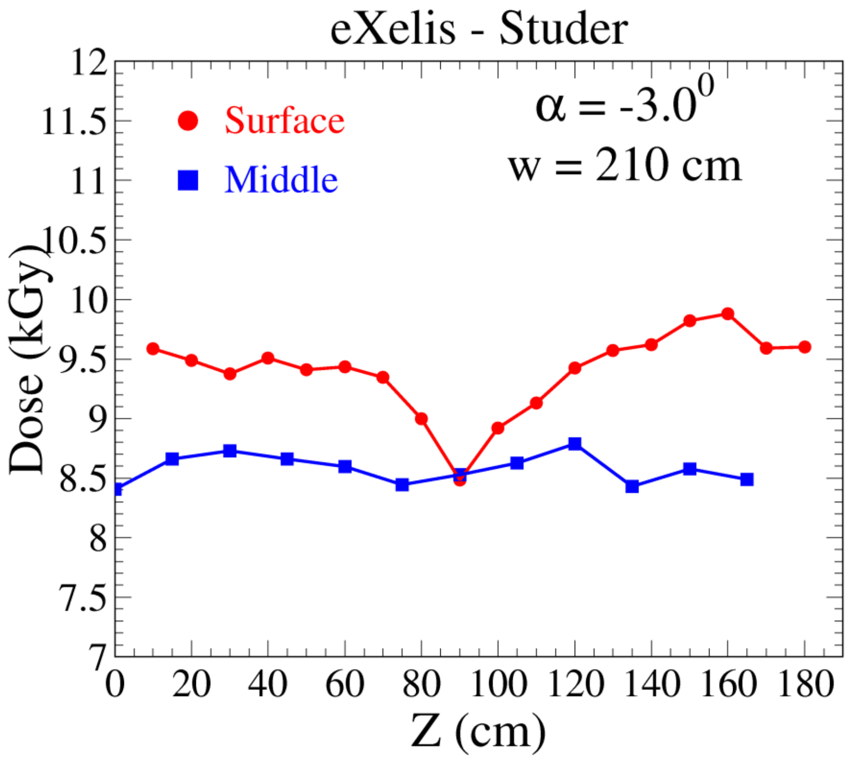
Leoni Studer Hard Test Results

- Optimization of scanning width w performed for various convergence angles α.

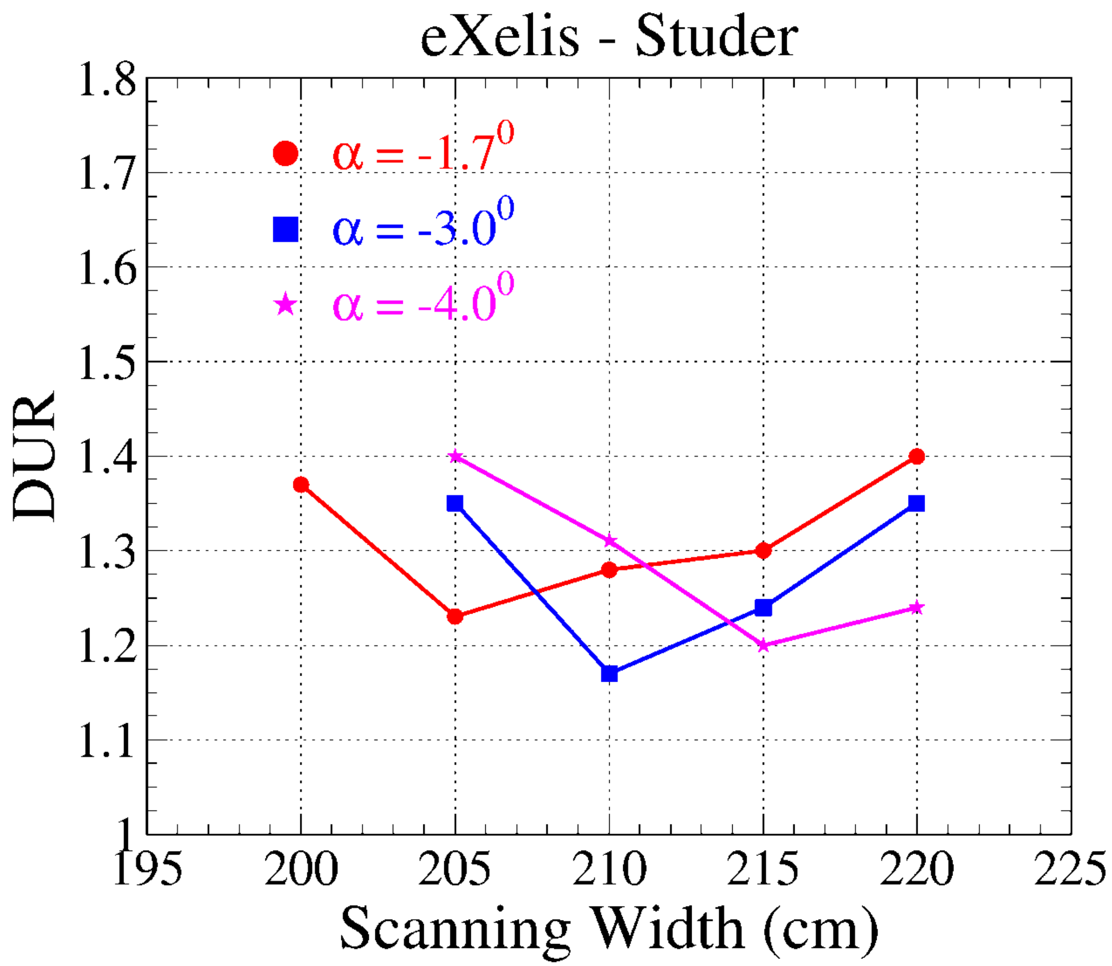
- When w is too small, bad overlap between dose distributions obtained in upper and lower level irradiations ➔ hole at the pallet mid-height

- When w is too large, the bad overlap leads to the apparition of a peak in the pallet mid-height

Optimal situation



Leoni Studer Hard Test Results



➔ **For α = -3° and w = 210 cm: <u>DUR = 1.17</u>**

Leoni Studer Hard Test Results

The minimum value, 1.17, of the dose uniformity ratio, DUR, in a full pallet load at a density of 0.15 g/cu cm is an encouraging result for X-ray processing. It is better than the value of 1.45 measured with the same pallet load density in a cobalt-60 gamma-ray irradiator.

For the same maximum dose, the minimum dose with X-rays will be higher than with gamma rays by a factor Of 1.45 / 1.17 = 1.24. Therefore, the processing rate with X-rays will be higher than with gamma rays by this ratio for the same emitted power.

Conclusion

The recent improvements of high-energy, high-power electron accelerators have made X-ray processing a practical alternative to gamma-ray processing for any application that requires greater penetration than can be provided by energetic electron beams.

The feasibility of radiation processing with high-energy X-rays has already been demonstrated in industrial facilities in several countries, including the USA, Japan, France and Germany.

Conclusion

Economic comparisons have shown that the capital costs and electric power costs of high-power electron accelerators with electron energies in the 5 to 7 MeV range can be lower than the capital costs and source replenishment costs for Co-60 source loadings greater than about 2 MCi.

The greater penetration of high-energy X-rays allows the processing of full pallet loads of products. This reduces the labor costs and the risk of misplacing or damaging products while transferring them from pallets to smaller totes for processing.

Conclusion

Shipping, installation, operation, maintenance and disposal requirements for X-ray equipment are simpler than those for large radioactive sources.

The ability to change the radiation intensity and to turn off the radiation source when not needed are attractive features of an accelerator facility for X-ray processing.

When the electricity comes from a nuclear power plant, then X-ray processing is another practical application of nuclear technology. But the radioactivity can be left inside the power plant, and the electrical power can be converted back to ionizing energy where it is needed.

Thank you!