Accelerators for medical and industrial applications

JUAS Archamps, March 6th 2018

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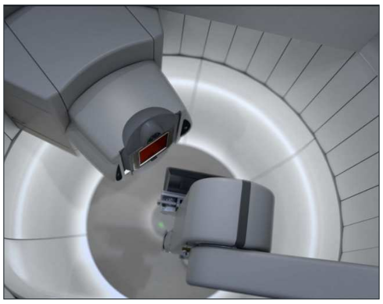
Organization of the lecture

- Intro and Overview
- Part 1: Radioisotopes for medical applications
- Part 2: Cyclotron design and beam dynamics
- Part 3: Particle therapy systems for cancer treatment

Protect, Enhance and Save Lives

IBA – Ion Beam Applications



MEDICAL TECHNOLOGY

- PROTON THERAPY (PT)
- DOSIMETRY
- RADIOPHARMA SOLUTIONS
- INDUSTRIAL APPLICATIONS

Protect, Enhance and Save Lives

NOWADAYS

- **R&D:**
  - 12% of turnover
  - 13% of workforce
- **Patent portfolio** (2016):
  - 510 patents & patent applications, for 102 innovations
- Over **400 accelerator** systems installed worldwide
- **~270 M€ sales** in 2015
  - ~1600 employees worldwide, 40 nationalities

Radiological Use of Fast Protons

ROBERT R WILSON
Research Laboratory of Physics, Harvard University Cambridge, Massachusetts
Accepted for publication in July 1946.

Except for electrons, the particles which have been accelerated to high energies by machines such as cyclotrons or Van de Graaff generators have not been directly used therapeutically. Rather, the neutrons, gamma rays, or artificial radioactivities produced in various reactions of the primary particles have been applied to medical problems. This has, in large part, been due to the very short penetration in tissue of protons, deuterons, and alpha particles from present accelerators.

Higher-energy machines are now under construction, however, and the ions from them will in general be energetic enough to have a range in tissue comparable to body dimensions. It must have occurred to many people that the particles themselves now become of considerable therapeutic interest. The object of this paper is to acquaint medical and biological workers with some of the physical properties and possibilities of such rays.

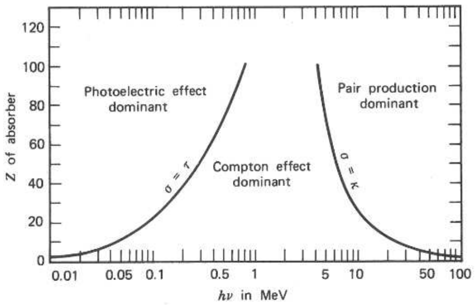
To be as simple as possible, let us consider only high-energy protons: later we can generalize to other particles. The accelerators now being constructed or planned will yield protons of energies above 125 MeV (million electron volts) and perhaps as high as 400 MeV. The range of a 125 MeV proton in tissue is 12 cm., while that of a 200 MeV proton is 27 cm. It is clear that such protons can penetrate to any part of the body.

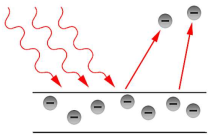
Hadron Therapy?

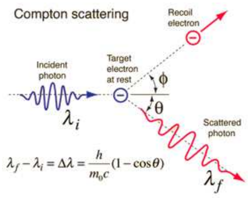
Short Introduction

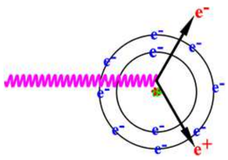
« Conventional » radiation therapy vs. hadrontherapy

- Most conventional radiation therapy and arc therapy systems use xrays in the ~10 MeV range for cancer treatment
  - Dose is not delivered to tissues by the photons themselves, but rather through secondary electrons produced by 3 mechanisms









G.F. Knoll – Radiation detection and measurement, Wiley

Protect, Enhance and Save Lives

« Conventional » radiation therapy

- Results in:
  - A decrease of photon numbers following a superimposition of decreasing exponentials
  - Some electron buildup

=> dose builds-up and then ~exponentially decreases with depth once electron equilibrium is reached

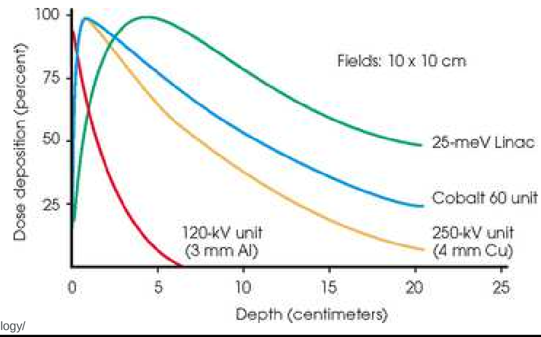


Image courtesy of http://radiologykey.com/radiation-oncology/

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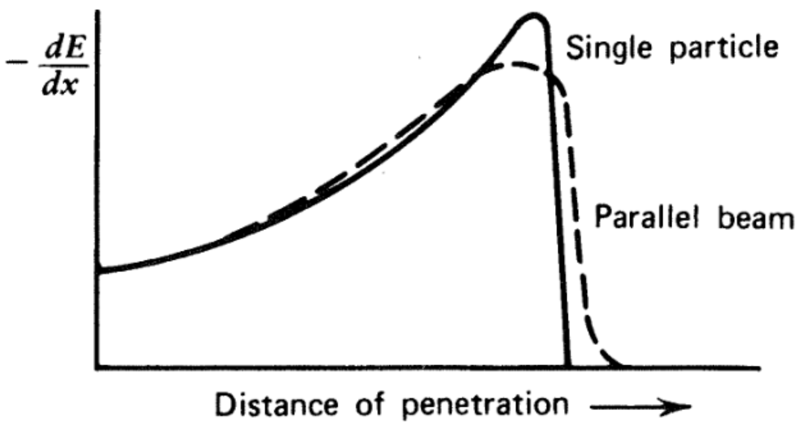
Hadrontherapy

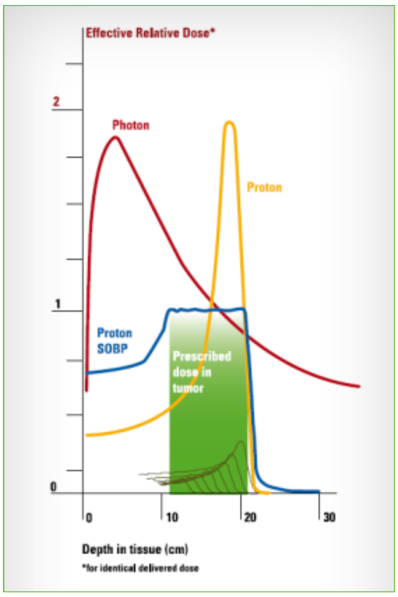
Results in the famous « bragg peak » dose distribution



G.F. Knoll – Radiation detection and measurement, Wiley

Protect, Enhance and Save Lives

As a result:



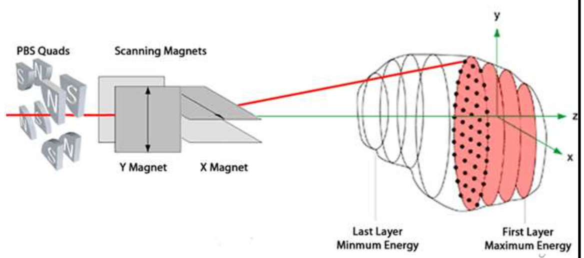
- Hadrons offer the following advantages:
  - Little radiation upfront the tumor
  - No/little radiation at all beyond the tumor

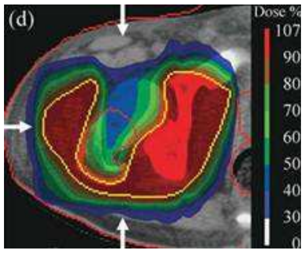
  => Lower integral dose per treatment
- Leading to potential clinical advantages:
  - Up to 50% reduced risk of radiation-induced secondary cancer
  - Drastically lower risk of adverse effects (treatment toxicity, side effects, growth abnormality) – better quality of life

Protect, Enhance and Save Lives

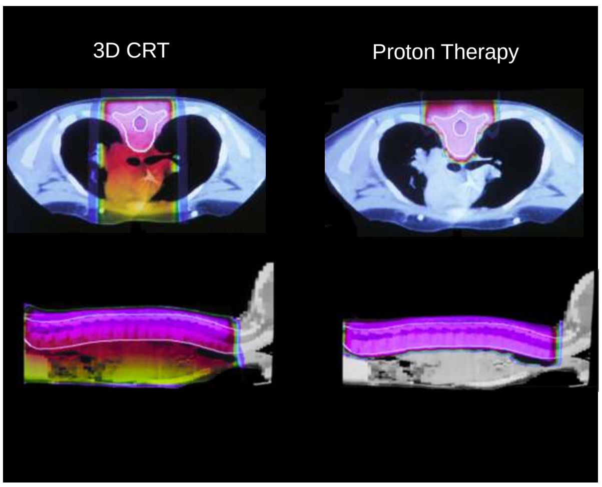
PBS – Pencil Beam Scanning

- Advantages:
  - Good 3D dose conformity
  - “Flexible”
  - Low neutron dose
  - No need for patient specific aperture
- Disadvantages:
  - Dynamic system, less safe than passive system
  - Layer by layer, slower than scattering
  - Lateral penumbra less sharp than with collimation





Pediatric medulloblastoma – Side effects



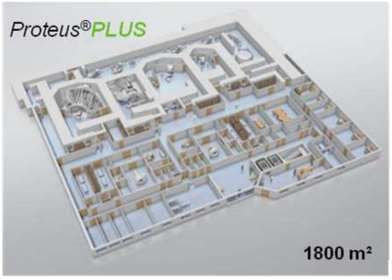
Side Effects	Protons	Photons
Restrictive Lung Disease	0%	60%
Reduced exercise capability	0%	75%
Abnormal EKGs	0%	31%
Growth abnormality	20%	100%
IQ drop of 10 points at 6 yrs	1.6%	28.5%
Risk of IQ score < 90	15%	25%

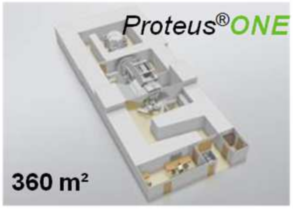
“Proton beam therapy has become a standard of care for pediatric cancers… ” (*)

(*) Presentation Dr. Jay S. Loeffler, NPTC/MGH, ASTRO 2001

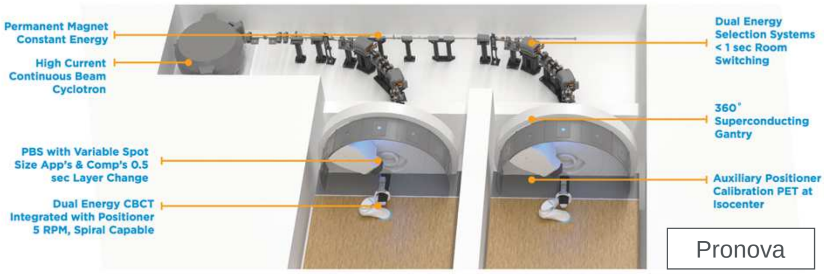
Typical proton therapy systems

IBA





Mevion

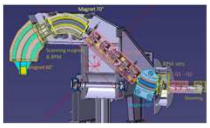


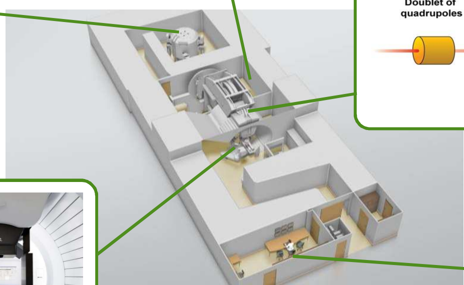
Pronova

Major components (IBA ProteusONE)

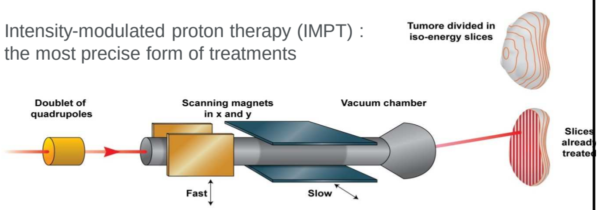
Compact super-conducting accelerator for producing the energetic proton beam

A rotating gantry to set the beam at the right angle

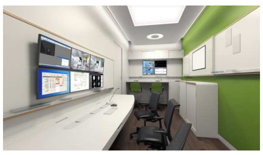




Intensity-modulated proton therapy (IMPT) : the most precise form of treatments



Stereoscopic imaging and CBCT at isocentre:
accurate patient setup,
quality images for adaptive treatments



Efficient software integration,
enabling easy & flexible workflows

Accelerators in PT

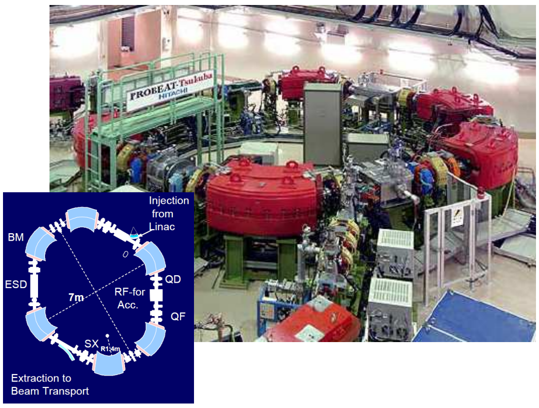
- (rough) requirements
  - Max. energy: 230 (250 MeV) protons – 400 MeV/u carbon ions
  - Min energy: ~70 MeV protons
  - At least 2 Gy/l/min => a few nA average beam current at nozzle level
  - Fast beam intensity modulation
  - Minimum footprint
  - Minimum energy consumption
- Currently available on the market
  - Synchrotrons
    - Beam accelerated on a single path, magnetic field is ramped

    =>Variable energy, pulsed beam, multiple-stage
  - Cyclotrons and synchro-cyclotrons
    - Acceleration on a spiral path, fixed magnetic field

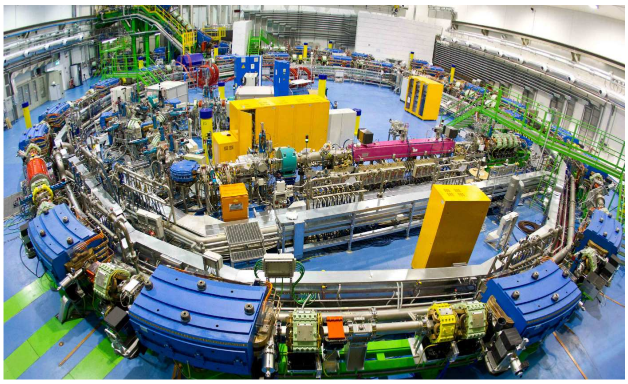
    => Usually fixed energy, CW or pulsed (high rep. rate), single stage
- Potential (far) future developments:
  - Linacs
  - Wakefield accelerators
  - Cyclinacs

  Trend: variable-energy

Synchrotrons



Hitachi
- 70-250 MeV protons
- Slow cycle
- 7 m Diameter



"PIMMS" (CERN) design
- Up to Carbon
- 25 m Diameter
- Rep. rate: 5 Hz
- Installed @CNAO, Medaustron

http://www.protominternational.com/about/about-radiance-330/

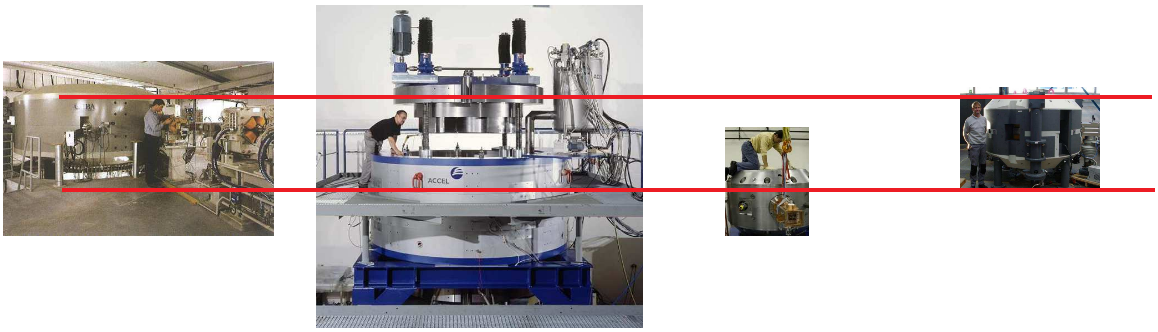
Rossi, EurPhysJPlus2011-126-78.pdf

Trend: more compact

Protom
- Up to 330 MeV protons
- 5 m Diameter, ~16 tons
- Being installed @MGH

http://www.protominternational.com/about/about-radiance-330/

Cyclotrons in PT – commercial models



IBA C230
- 230 MeV protons
- 4.3 m Diameter
- CW beam
- Normal conducting
- Magnet: 200 kW
- RF: 60 kW

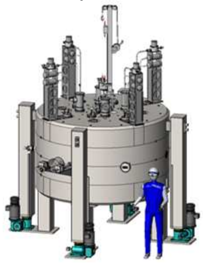
Varian-Accel Probeam
- 250 MeV protons
- 3.1 m Diameter
- CW beam
- Superconducting (NbTi)
- Magnet: 40 kW
- RF: 115 kW

Mevion SC250
- 250 MeV protons
- ~1.5 m Diameter (shield)
- Superconducting (Nb_3Sn)

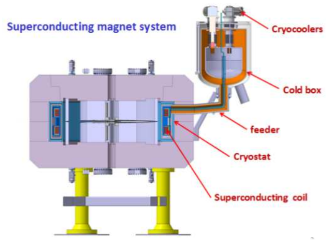
IBA S2C2
- MeV protons
- 2.2 m Diameter
- Rep. rate: 1 kHz
- Superconducting (NbTi)
- RF: 11 kW

Proton cyclotrons - Ongoing developments

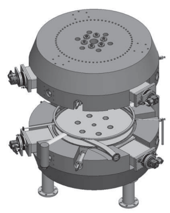
- 1. Isochronous: SHI, Varian/Antaya, Pronova/Ionetix, Heifei/JINR



Derenchuck - NAPAC 2016



Karamysheva - THP20 cyclotrons 2016



Antaya – CAS 2015

SHI
- 230 MeV protons
- 2.8 m Diameter
- CW beam
- Superconducting (NbTi)
- 55 tons
- 4 T (extr.)

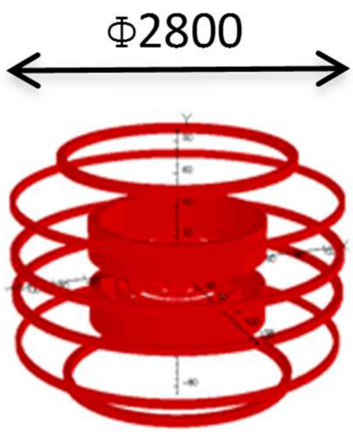
Pronova/Ionetix
- 250 MeV protons
- 2.8 m Diameter
- CW beam
- Superconducting (Nb_3Sn)
- 60 tons
- 3.7 T (extr)

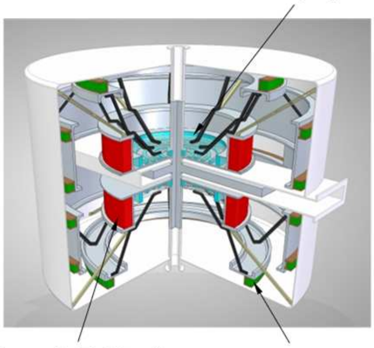
Heifei/JINR
- 200 MeV protons
- 2.2 m Diameter
- CW beam
- Superconducting
- 30 tons
- 3.6 T (extr.)

Varian/Antaya
- 230 MeV protons
- 2.2 m Diameter
- CW beam
- Superconducting (Nb_3Sn)
- 30 tons+
- 5.5 T (extr.)
- “Flutter” coils

Proton cyclotrons - Ongoing developments

- 2. Synchrocyclotrons: MIT ironless (Pronova)





- 250 MeV protons
- (2.4-)2.8 m Diameter
- Pulsed beam
- Superconducting (Nb_3Sn)
- 4 tons
- T (extr.)
- Cost?
- Variable-energy possible

Minervini – Ciemat workshop 2016

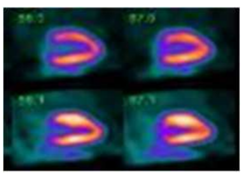
Radio-isotopes

Short Introduction

RadioPharma Solutions

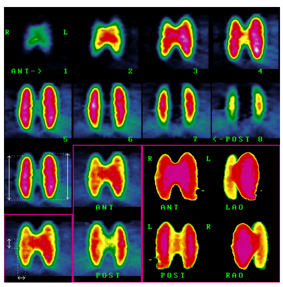
- **Making severe diseases diagnosis and therapy more accessible everywhere**
- **by lowering production costs and complexity of radioisotope-labeled drugs**

Oncology
Na^{18}F Bone scan



Cardiology
Sr/Rb82
^{13}NH3
15O

Oncology
^{18}FDG & others



Oncology & others
^{123}I

Protect, Enhance and Save Lives

A family of cyclotrons for isotope producion

- Cyclone 3D 3 MeV D+ (production of Oxygen-15)

Enabler Cyclone 11: 11 MeV H-, 120 µA (~1300 W)

Pet Production Cyclone 18/9: 18 MeV H-, 150 µA (~2700 W) Deuteron possible

Pet/SPECT crossover Cyclone 30(xp): 30 MeV, 1.2 mA (36 kW) alpha/deuteron possible (xp)

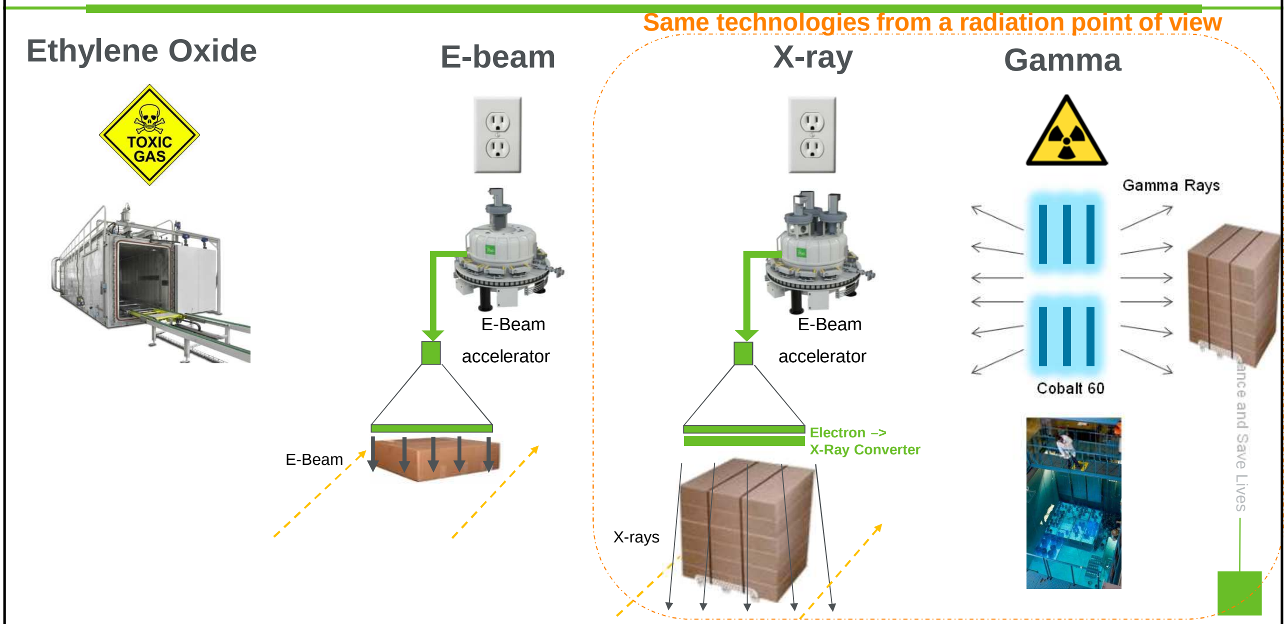
World record Cyclone 70(xp): 70 MeV, 750 µA (53 kW) alpha/deuteron possible (xp)

Protect, Enhance and Save Lives

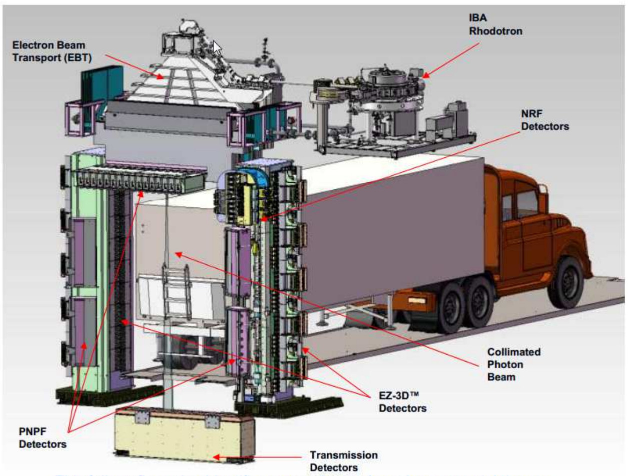
Industrial applications

Short Introduction

Sterilization Processing Comparison

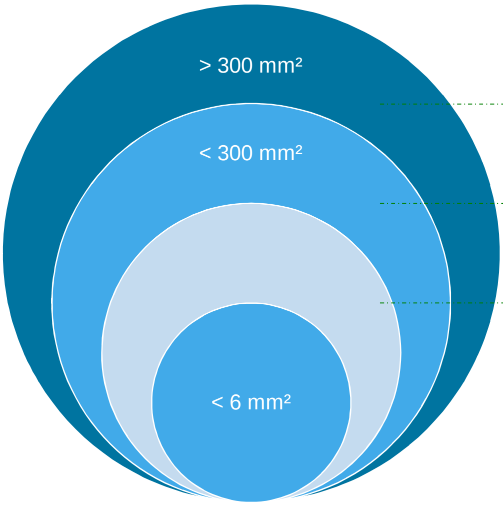


Cargo screening => TT50



This full configuration identifies anomalies and resolves potential threats

Cables treatment with electrons: Dynamitron => crosslinking

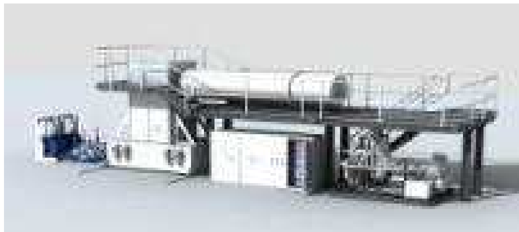


Not crosslinked with radiation

3 MeV
Multiple applications

1.5 MeV
Multiple applications

800 keV
Automotive



IBA Industrial's Product Portfolio

Dynamitron
0.5 -> 5 MeV | 160 mA
Electron beam

Main application
E-beam Crosslinking

Rhodotron
3 -> 10 MeV | 42 mA | 420 kW
Electron beam and X-rays

Main application
E-beam box sterilization

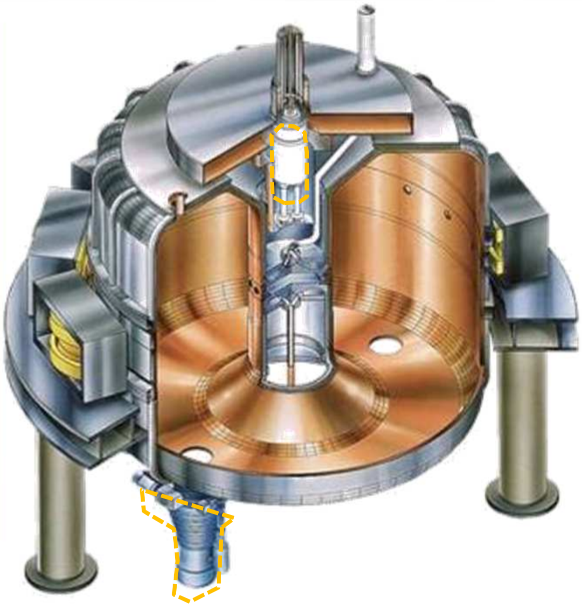
eXelis
5 – 7 MeV | 80 mA | 560kW
X-rays

Main application
X-ray pallet sterilization

Linac's reach about 40-60 kW

Brief explanation of the Rhodotron:

The main components

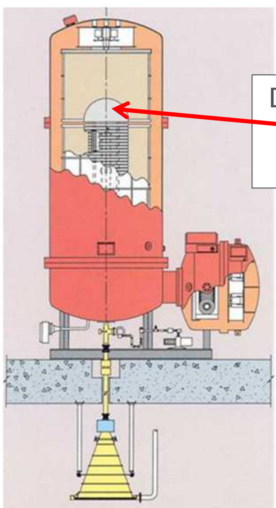


- RF Cavity
- E-Gun
- Magnets
- Final Power Amplifier

- RF tube (Tetrode)
- Vacuum system

Dynamitron

High Voltage generation => similar to a Cockcroft-Walton



Dees and rectifier stack
Dome
SF6