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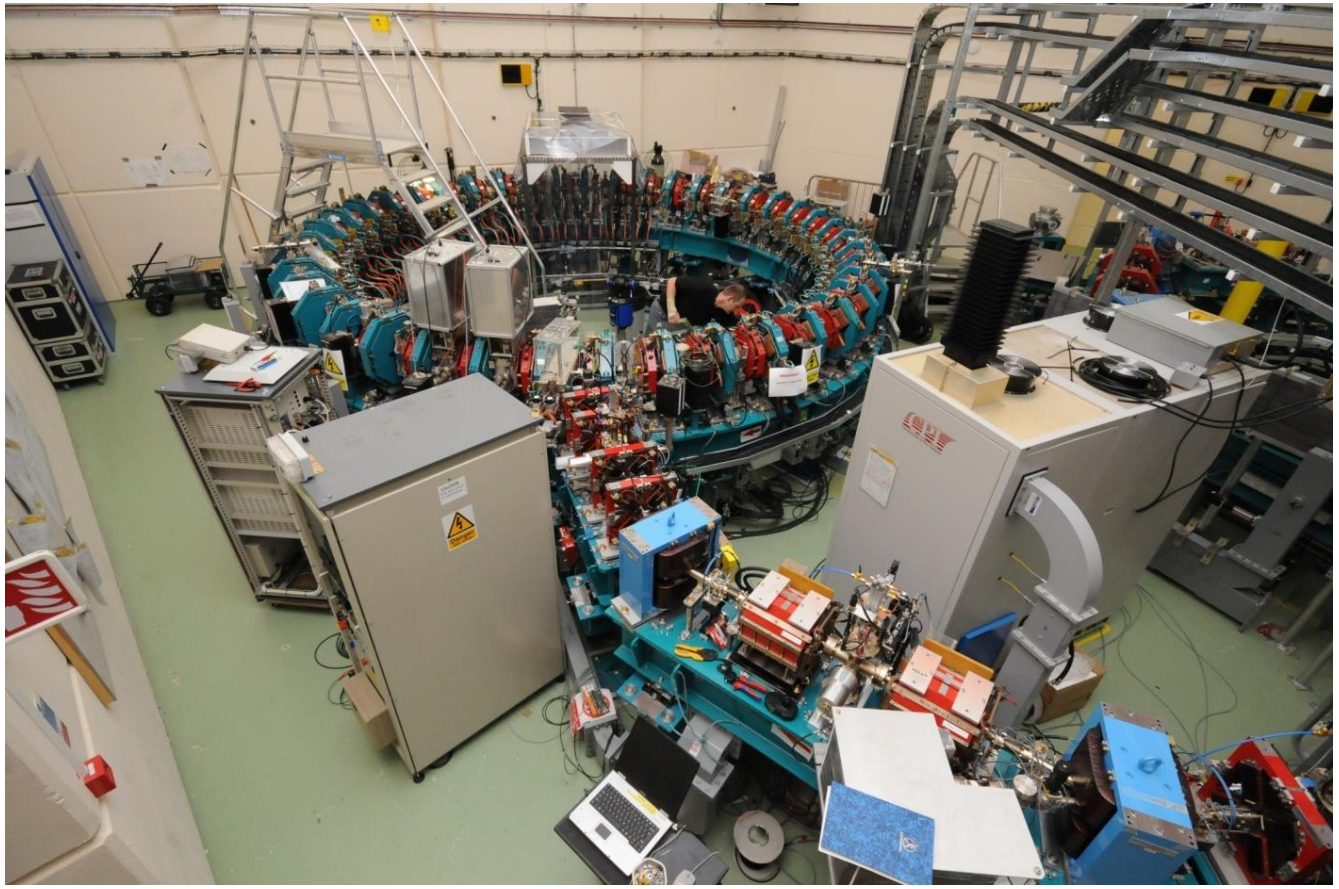
Applications of Accelerators

RAL 1957 2007
Celebrating 50 years of world class science

Prof Rob Edgecock
Rutherford Appleton Laboratory and
University of Huddersfield



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Outline

- Introduction to particle accelerators
  - at CERN
  - used for applications
- Summary of accelerator applications outside research
- Energy applications

- Medical applications:
  - cancer therapy

  - radioisotope production
- Industrial applications
- Environmental applications

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Radioisotopes

- Used for imaging:
  - Positron Emission Tomography (PET)
  - Single Particle Emission Computed Tomography (SPECT)
- Therapy:
  - brachytherapy
- Process:
  - produce the isotope
  - extract and purify it
  - bind it to pharmaceutical
  - introduce into patient
  - decay used for imaging/therapy

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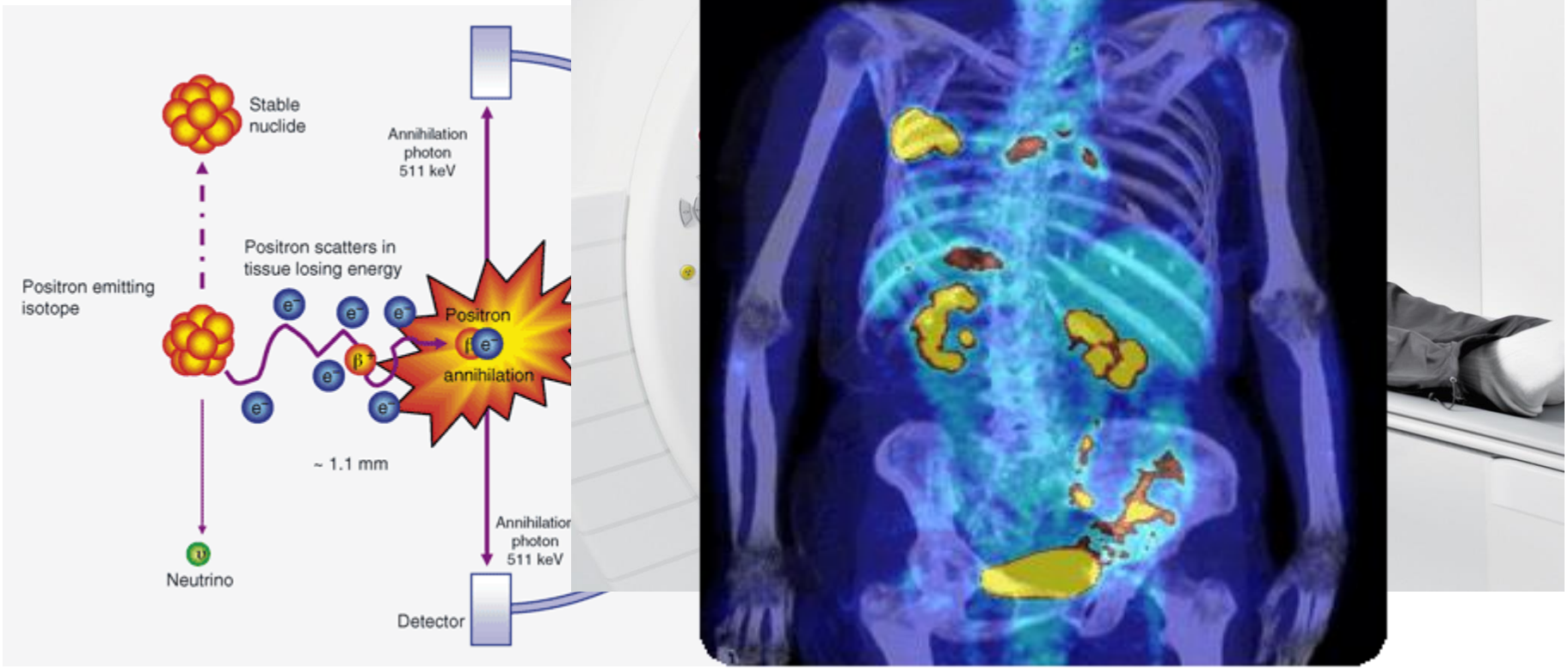
Radioisotopes

Two main diagnostic radioisotopes:

PET



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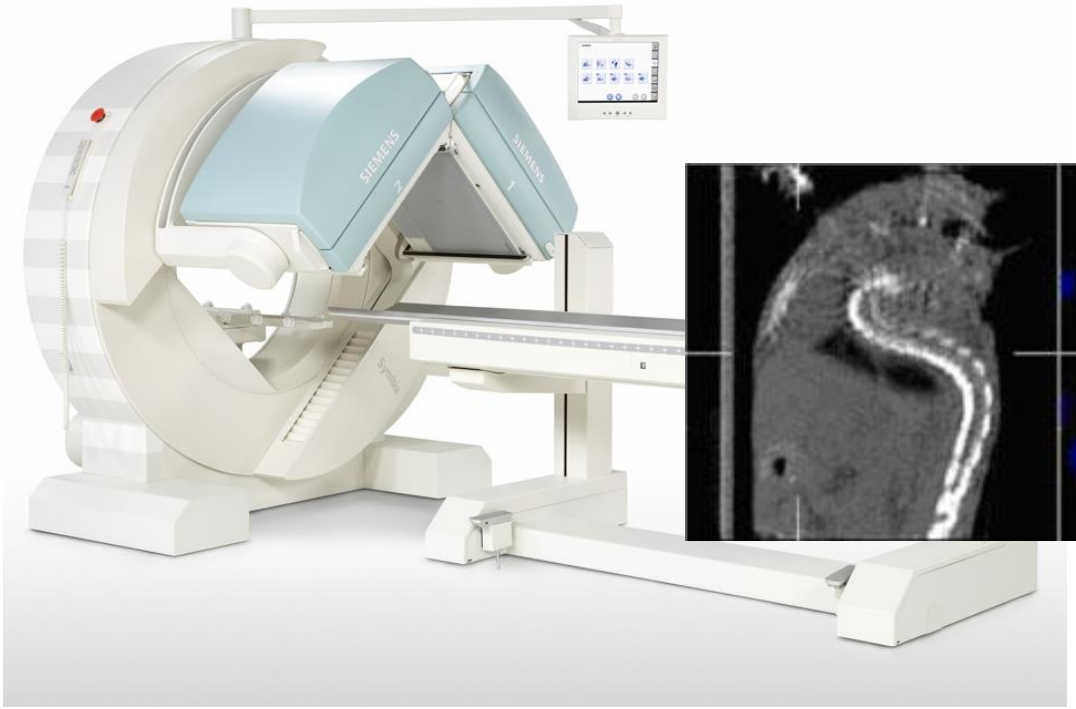
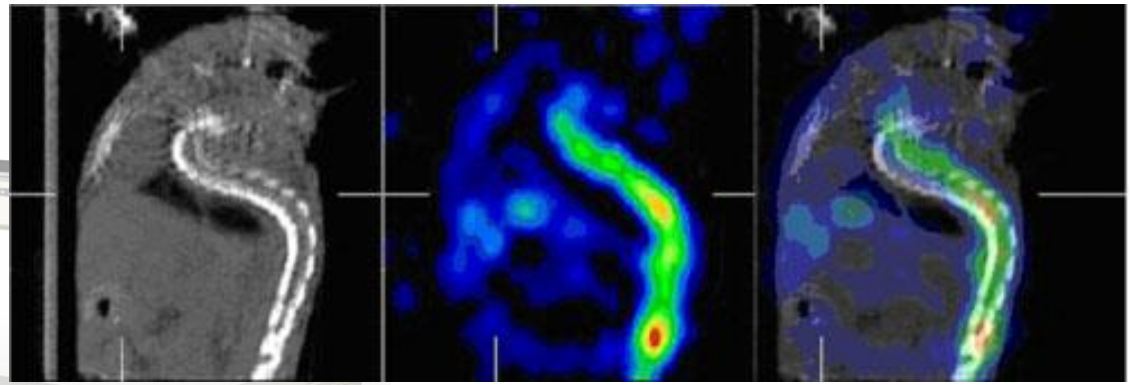
Radioisotopes

Two main diagnostic radioisotopes:

Single photon emitters - SPECT





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Nuclear Imaging

- Requirements
  - Must go where the want them
  - Must emit photons that can be detected
  - Half-life long enough for handling
  - Short enough that they don't last too long
  - Manufacture costs not too high
- Used currently most often:
  - SPECT: ^{99m}Tc – 140 keV photons, 6 hour half-life
  - PET: ^{18}F – 2*511 keV photons, 2 hour half-life

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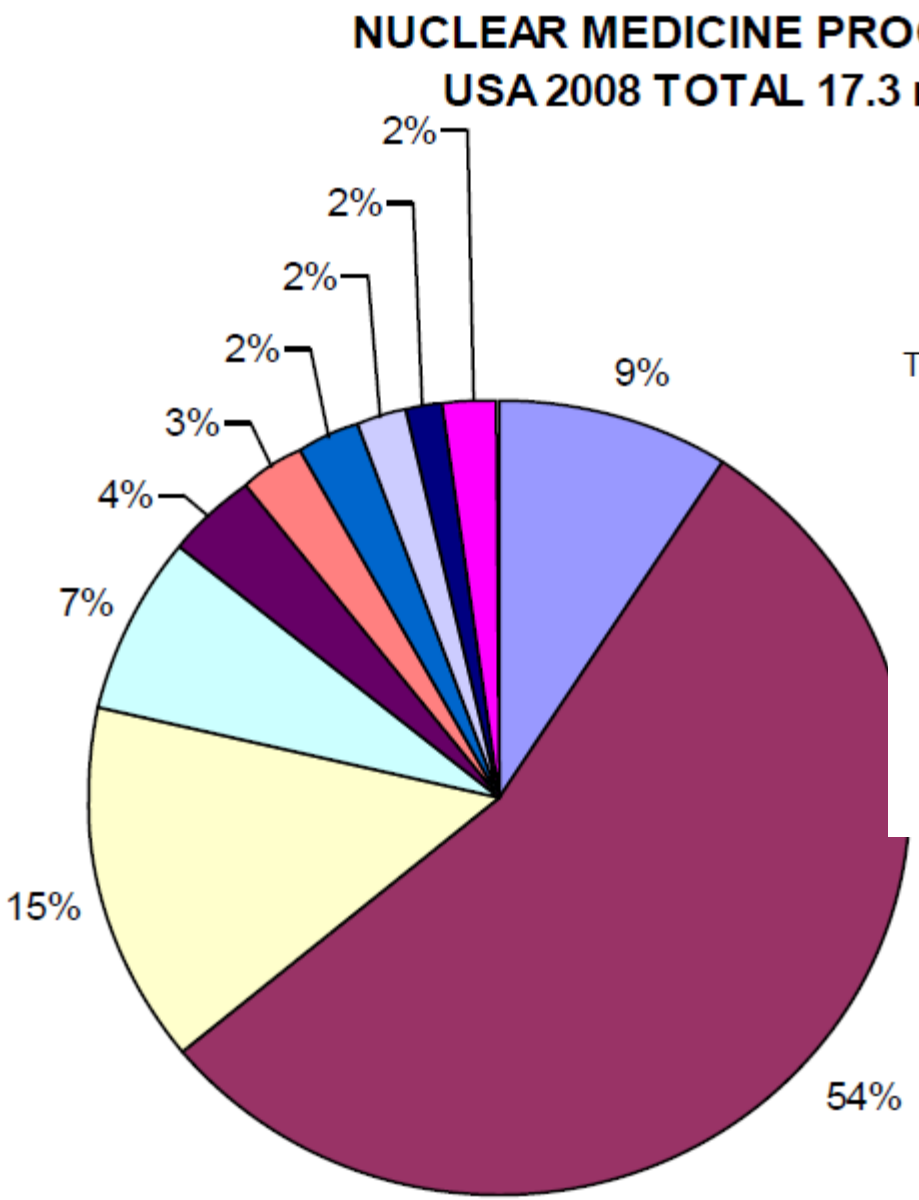
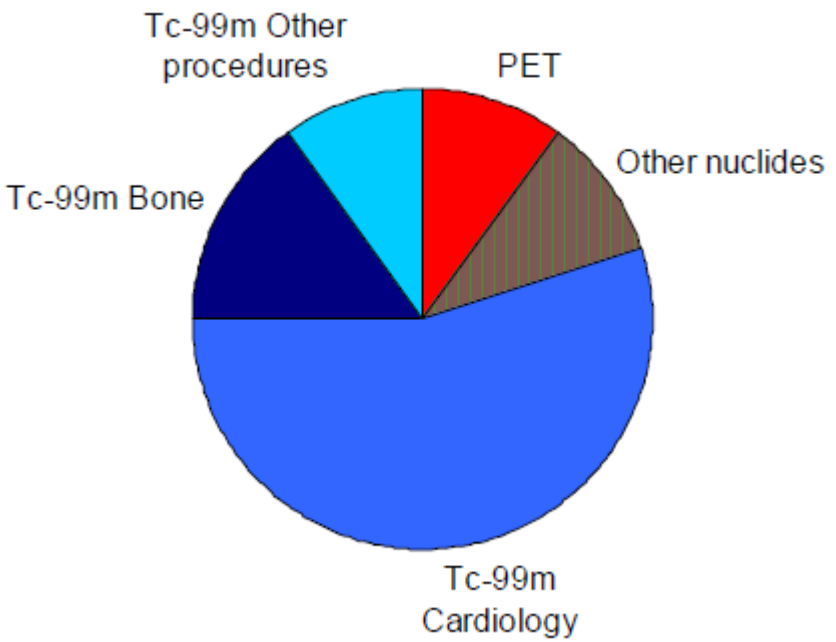
Status





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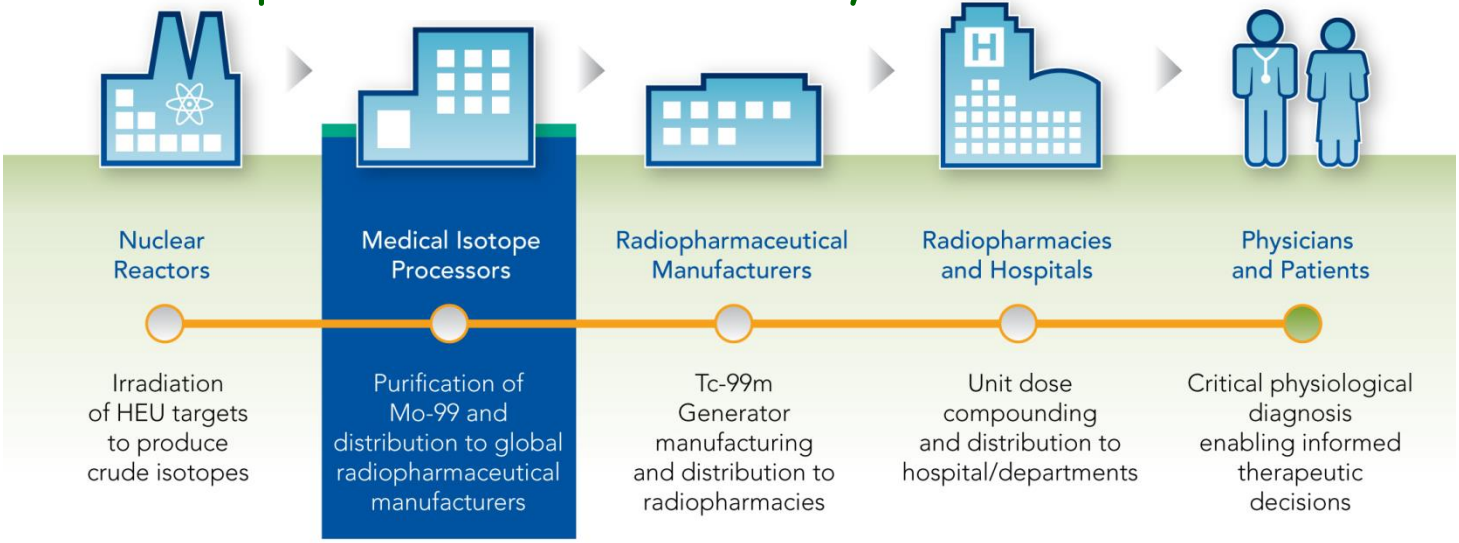
^{99m}Tc Production

- Made in (test) nuclear reactors
  - ^{99}Mo produced by fission of HE ^{235}U
  - ~6% of fission reactions
  - Mo is extracted in hot cells
  - Purified
  - Loaded into a "generator"
  - 99mTc produced from Mo decay, half-life 66 hours



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^{99m}Tc Production

- Until recently, done in 5 aging reactors

Table 2.2 Research reactors used for large-scale production of ^{99}Mo

Reactor	Location	Date of first commissioning	Power (MW)	Operational days per year	Capacity (% of European needs)
NRU	Chalk River, Canada	1957	135	270	N/A
HFR	Petten, the Netherlands	1961	45	280	>100
BR2	Mol, Belgium	1961	100	140	>100 when operating
OSIRIS	Saclay, France	1966	70	180	~25 when operating
SAFARI	Pelindaba, South Africa	1965	20	310	N/A
OPAL *	Lucas Heights, Australia	2006	20	340	N/A
MARIA †	Swierk, Poland	1974	30	160	~10 when operating
LVR-15 †	Rez, Czech Republic	1957	10	210	~10

* Not yet exporting ^{99}Mo
† Began international supply of ^{99}Mo in 2010

- Variety of radiopharmaceuticals produced in hospital

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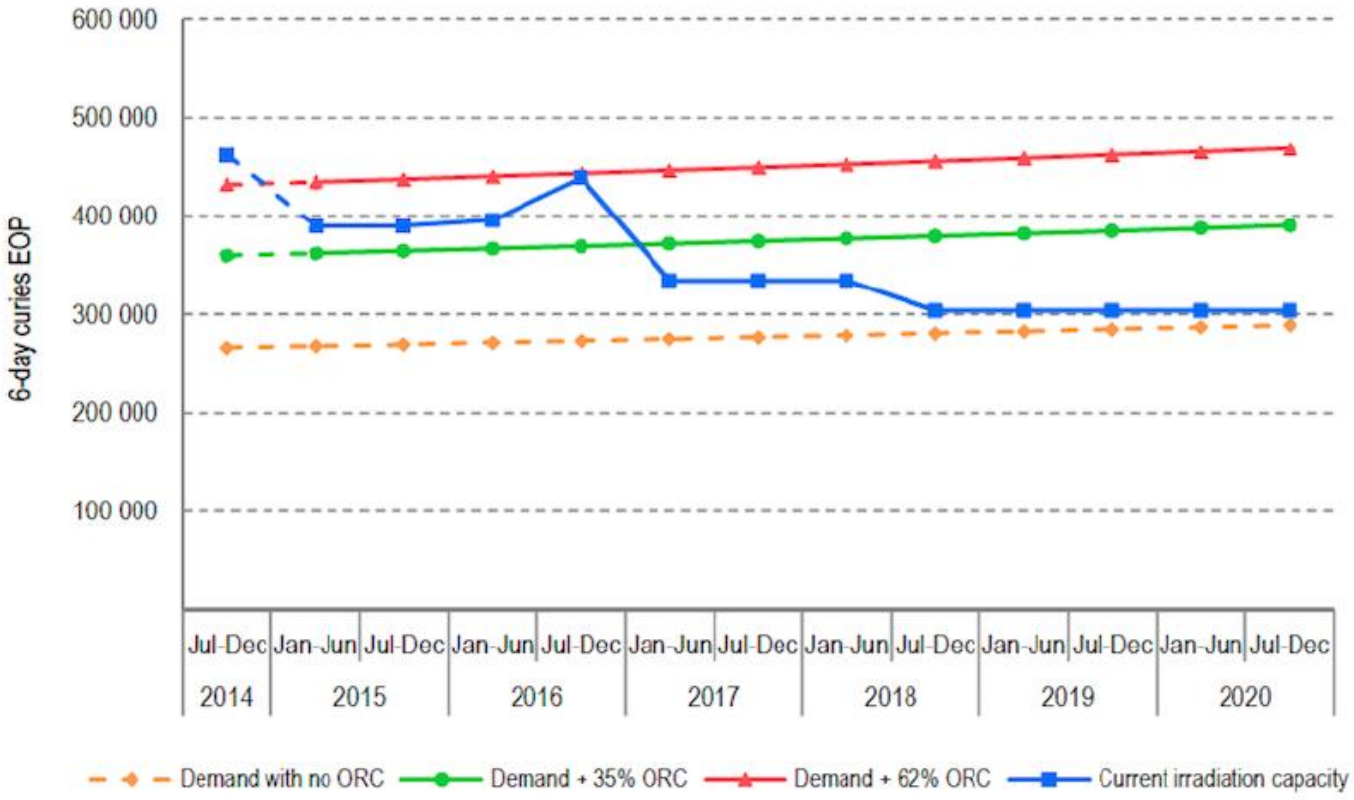
^{99m}Tc Production

- Well-known ^{99m}Tc problems due to (old) reactor production
  - Moly crisis in 2008/9
  - Potential shortage in ≥2016 due NRU closure & LEU



Various alternative production methods proposed, including accelerators

BNMS & STFC Report, December 2014

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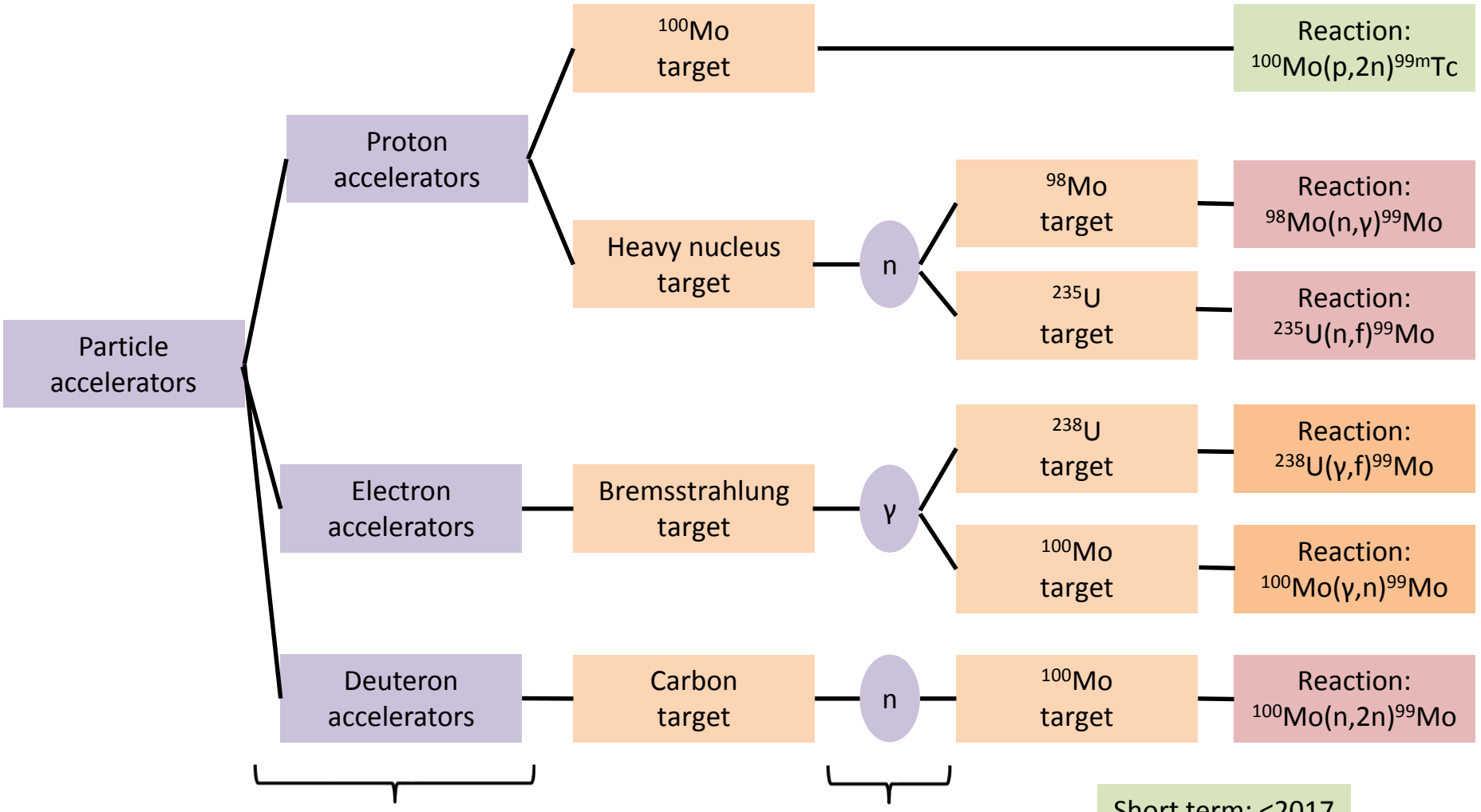
Accelerator Production



Short term: <2017

Med term: 2017-2025

Long term: >2025

Nuclear Energy Agency: direct production ^{100}Mo(p,2n)^{99m}Tc

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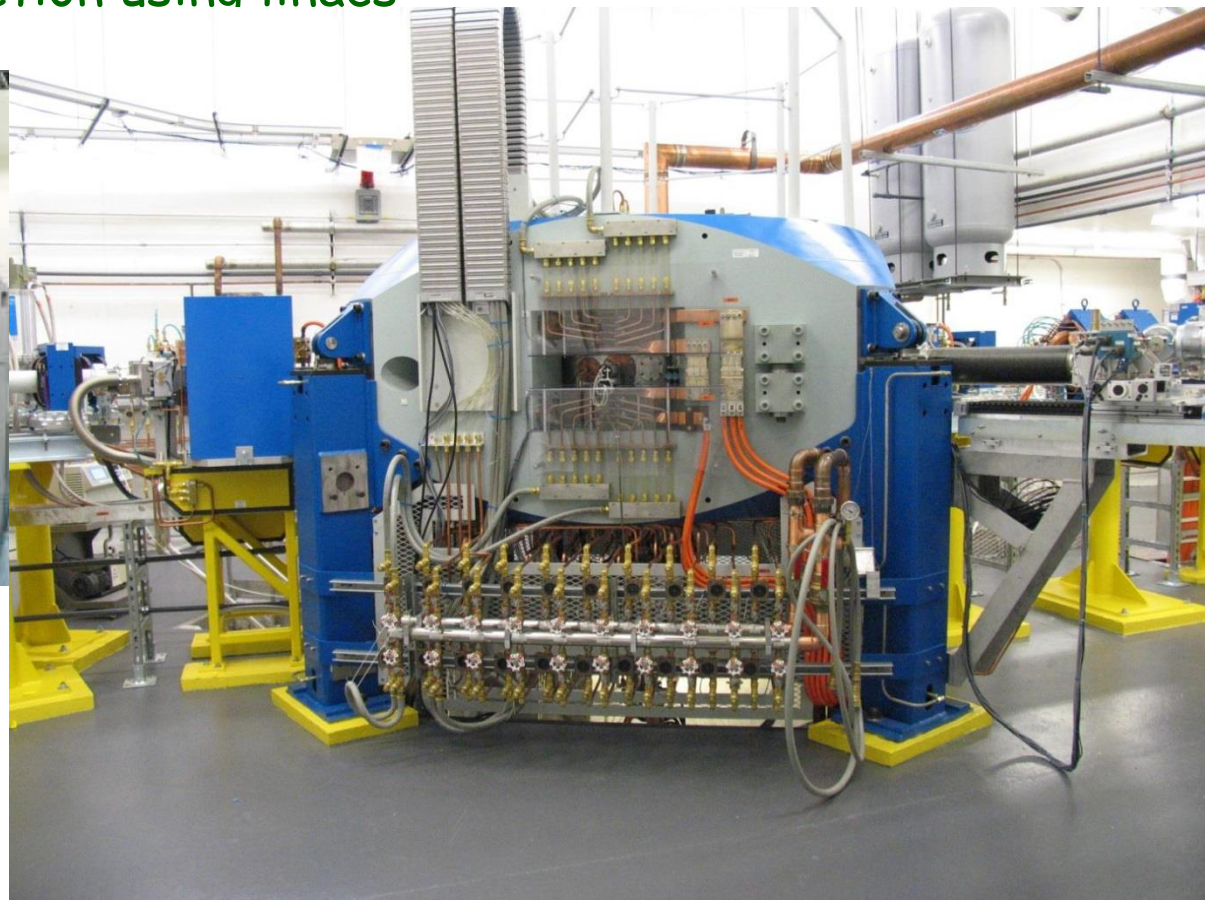
Accelerator Production

- Tests done, mainly in Canada:
  - direct production using cyclotrons
  - photo-production usina linacs

TR19: 14-19 MeV
~200 μA
Pop^{n} ~2.5M



TR24: 24 MeV, ~500 μA, pop^{n} ~4.5M

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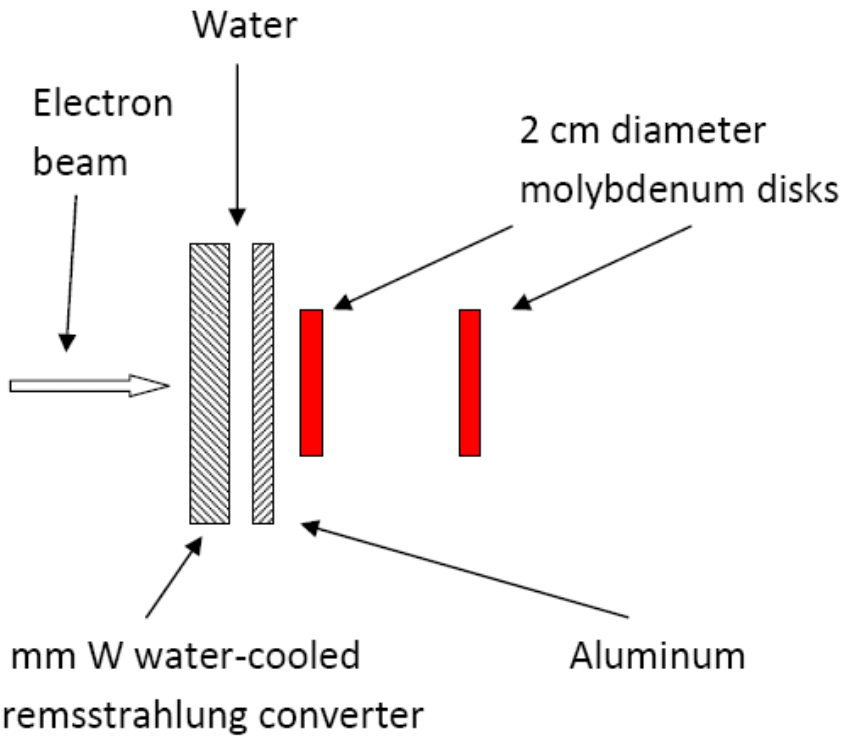
Accelerator Production

35 MeV, 2 kW test



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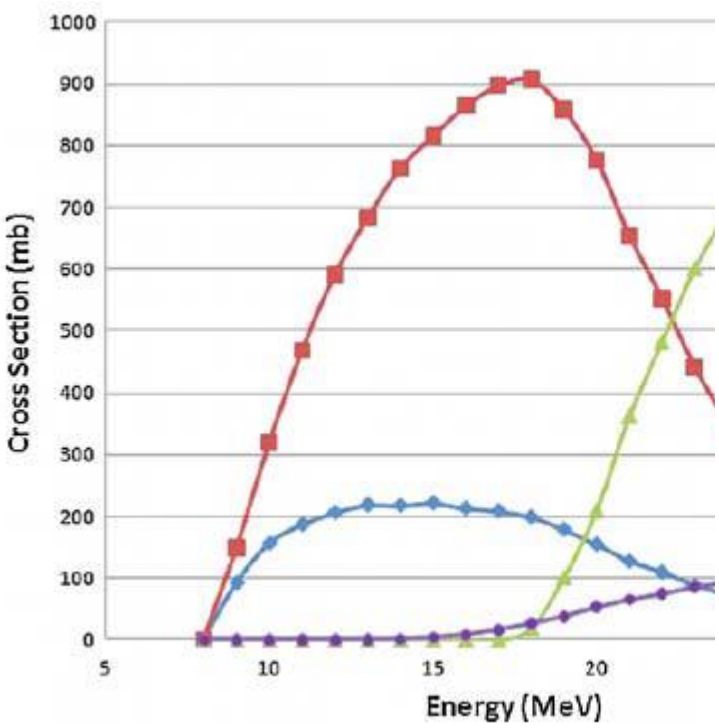
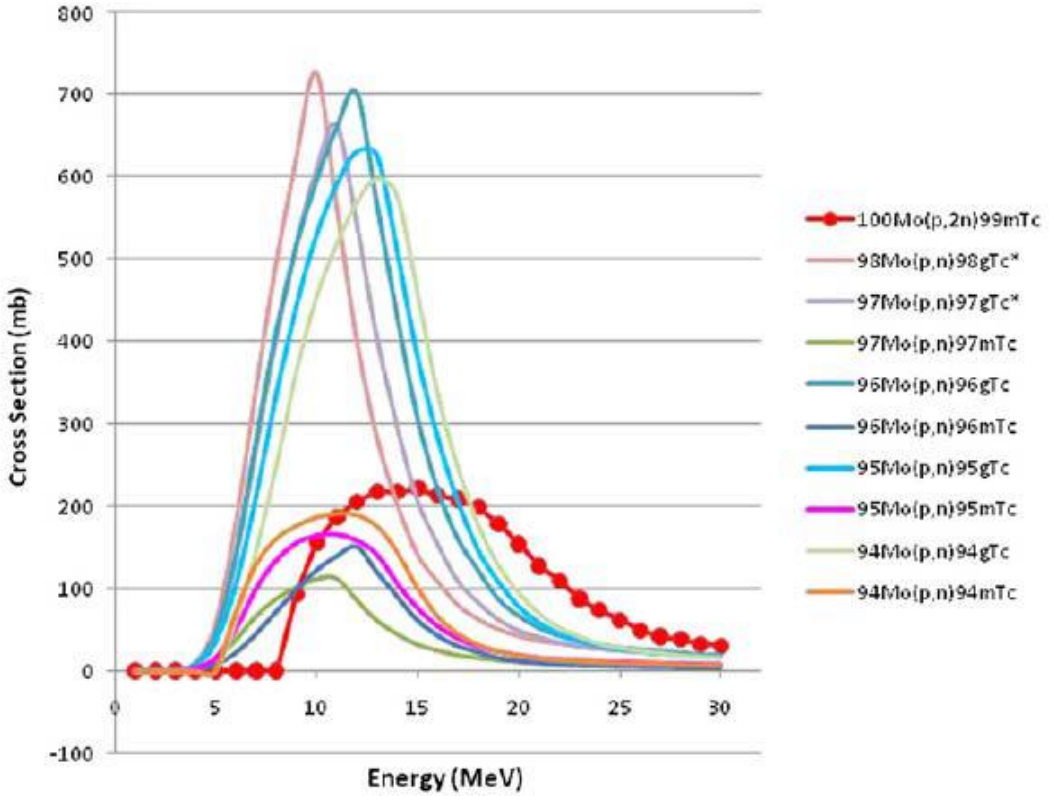
Accelerator Production

- Tests done, mainly in Canada:
  - direct production using cyclotrons
  - photo-production using linacs
- Technically looks feasible, but needs to be cost effective





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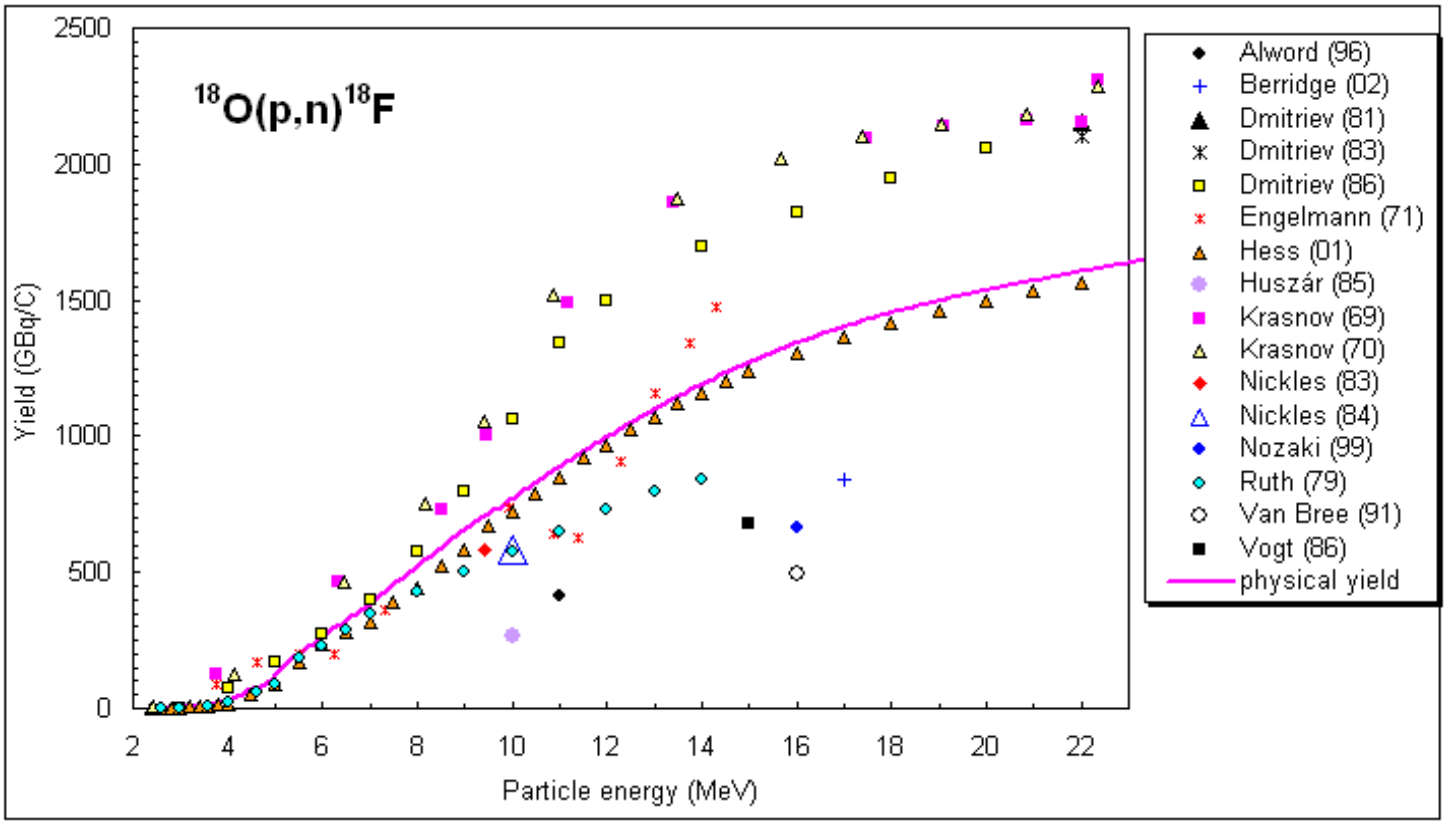
PET Production

- Pretty much all produced using a cyclotron
- Main isotope: ^{18}F
- Reaction: $^{18}O(p,n)^{18}F$
- ^{18}O enriched in water



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PET Production

		No of models	Lowest energy model (MeV)	Highest energy model (MeV)
IBA	Belgium	7	3	235
General Electric	Sweden	2	11	16
Siemens	USA	1	11	
ACSI	Canada	4	14	30
Best Medical	USA	4	14	70
KRIA	S Korea	2	13	30
Sumitomo	Japan	4	7	18
EuroMeV	France	1	12	
Efrimov Inst.	Russia	1	18	
CIAE	China	3	14	100

550 in 2007

Growing at ~50/year

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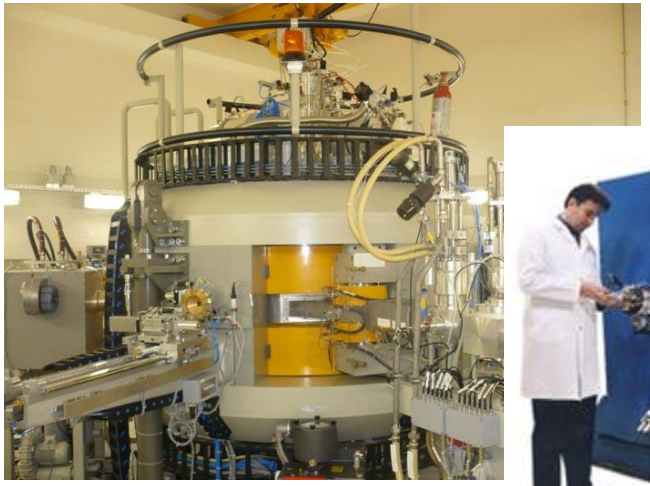
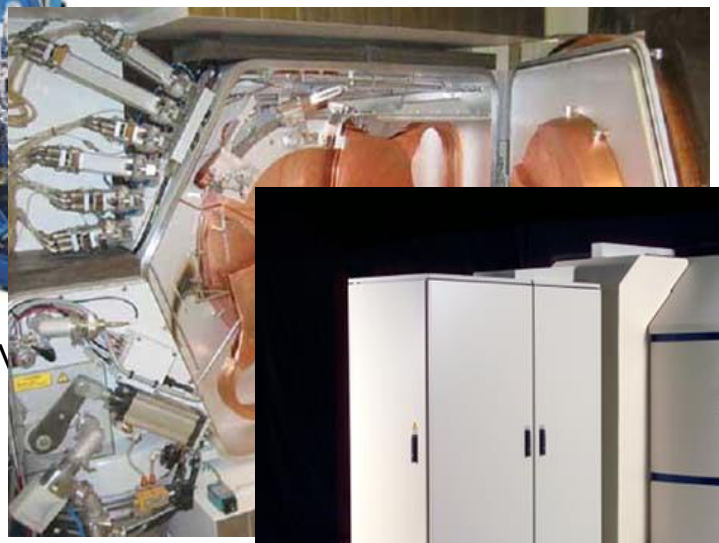
^{18}F Production

- Variety of cyclotrons used with variety of energies:



30 MeV, IBA

14-19 MeV



11 MeV, Siemens

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^{18}F Production

- Most widely used pharmaceutical by far:

  2-[18F]fluoro-2-deoxy-D-glucose (FDG)

- Usually produced centrally and shipped to hospital
- Much interest in shorter lived isotopes:
  - 11C: ~20 min – C in all biological molecules
  - 13N: ~10 min
  - 15O: ~2 min
- Must be produced locally
- Needs compact/cheap accelerators

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Alternative isotopes to ^{99m}Tc

- Replace ^{99m}Tc with other radioisotopes
- PET, e.g.
  ^{18}F, ^{82}Rb, ^{68}Ga, ?
- Other SPECT isotopes, e.g.
  ^{123}I, ^{87m}Sr, ^{113m}In, ^{81m}Kr, etc
- Potential problem: increased production costs
- Needs more cost effective accelerator production

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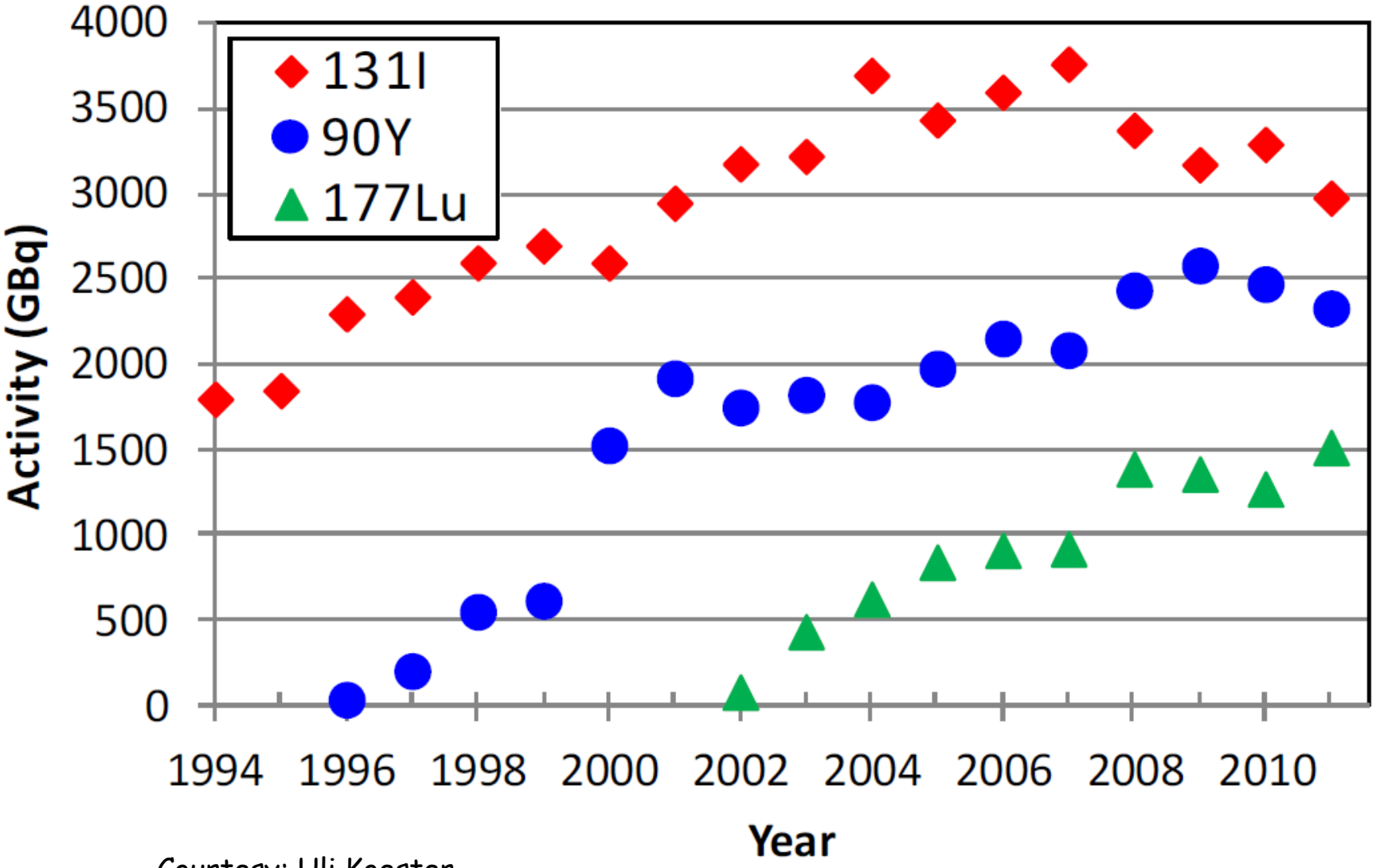
Therapeutic Radioisotopes



Courtesy: Uli Koester

Federal Office of Public Health, Bern, Switzerland

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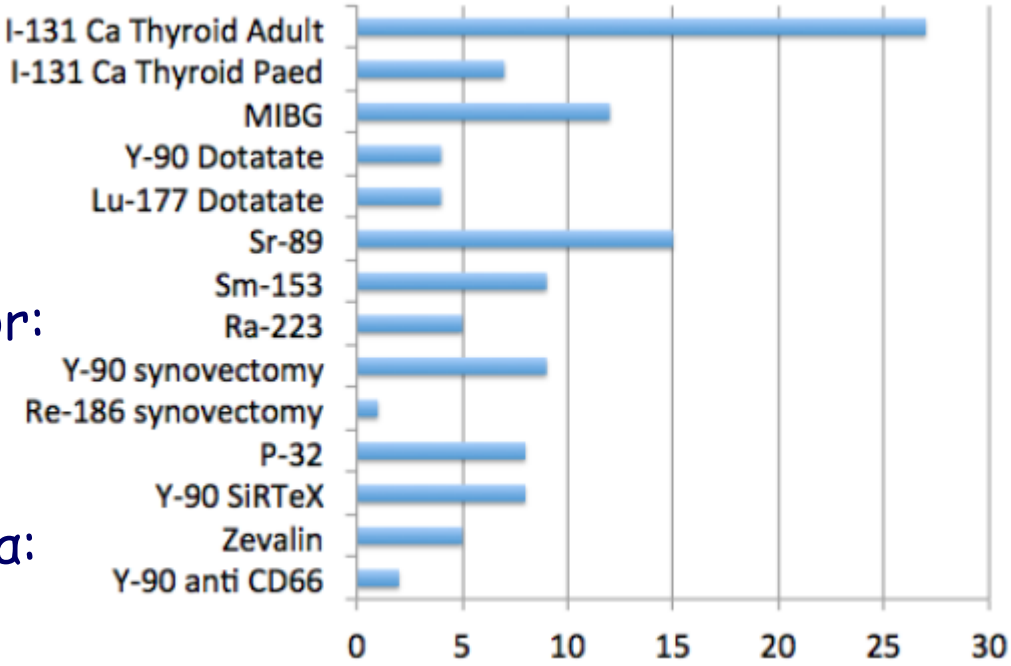
Therapeutic Radioisotopes

- Mainly reactor produced
- Supply can be a problem
- Some can be made by accelerator:
  - ^{177}Lu
  - ^{153}Sm
- Some interesting isotopes need a:
  ^{211}At, ^{67}Cu, ^{47}Sc
- Need to be cost effective:
  - right beam
  - right energy
  - high beam current



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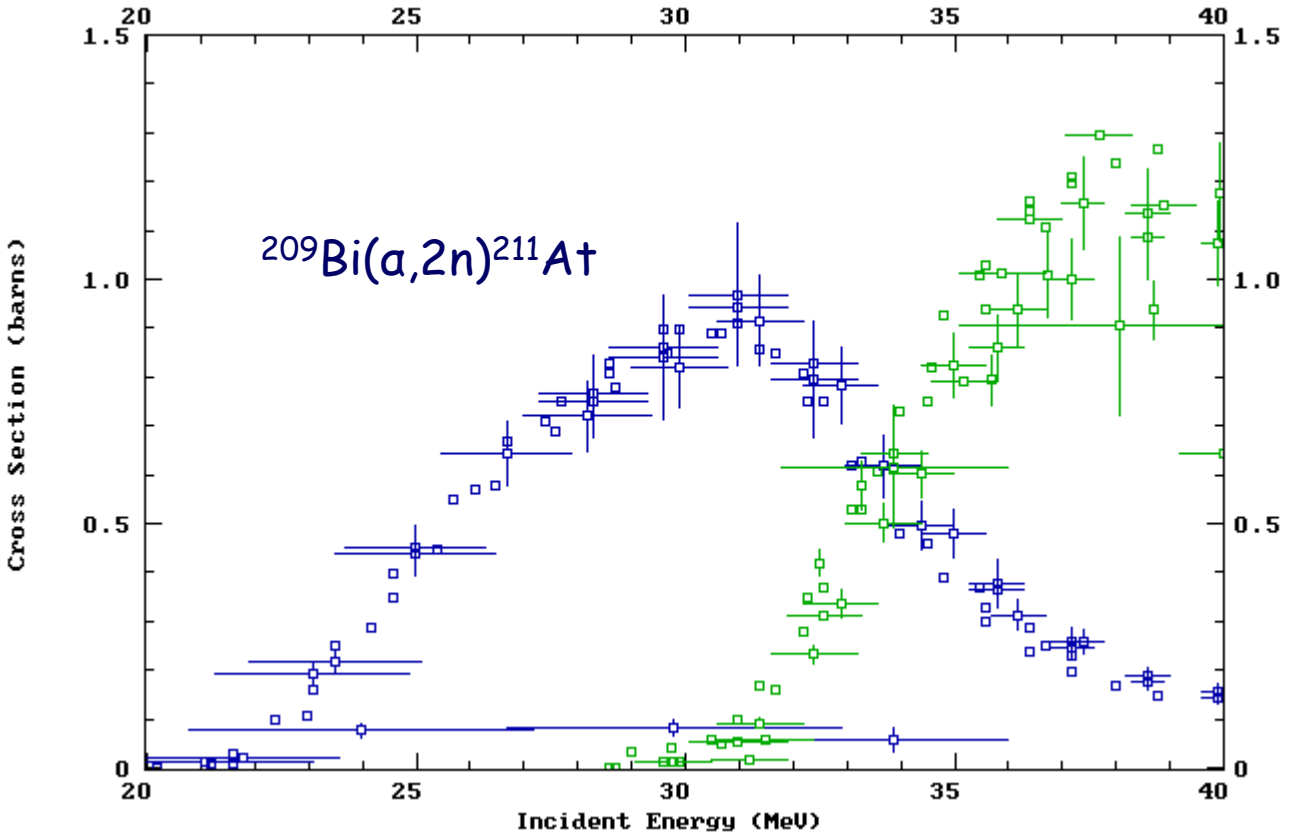
Therapeutic Radioisotopes



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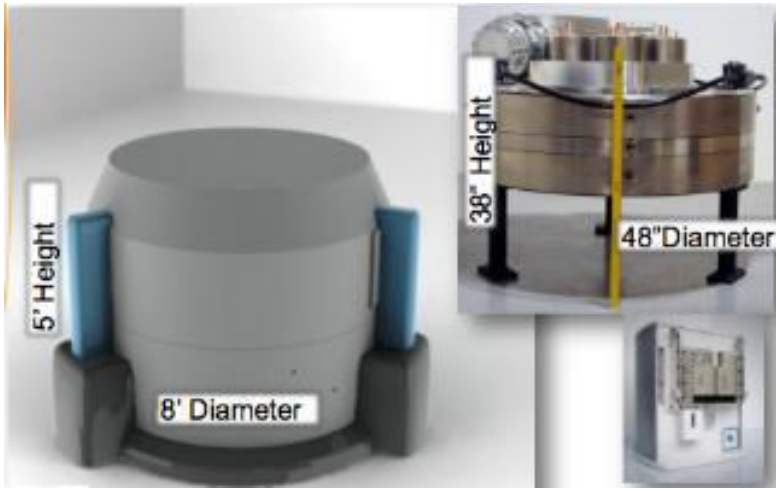
Developments to tackle issues

- Compact cyclotrons for patient-sized doses in hospitals
- For ^{18}F (2 hrs), but also ^{11}C (20 mins) and ^{15}O (2 mins)



ABT Molecular
7.5 MeV, 5µA

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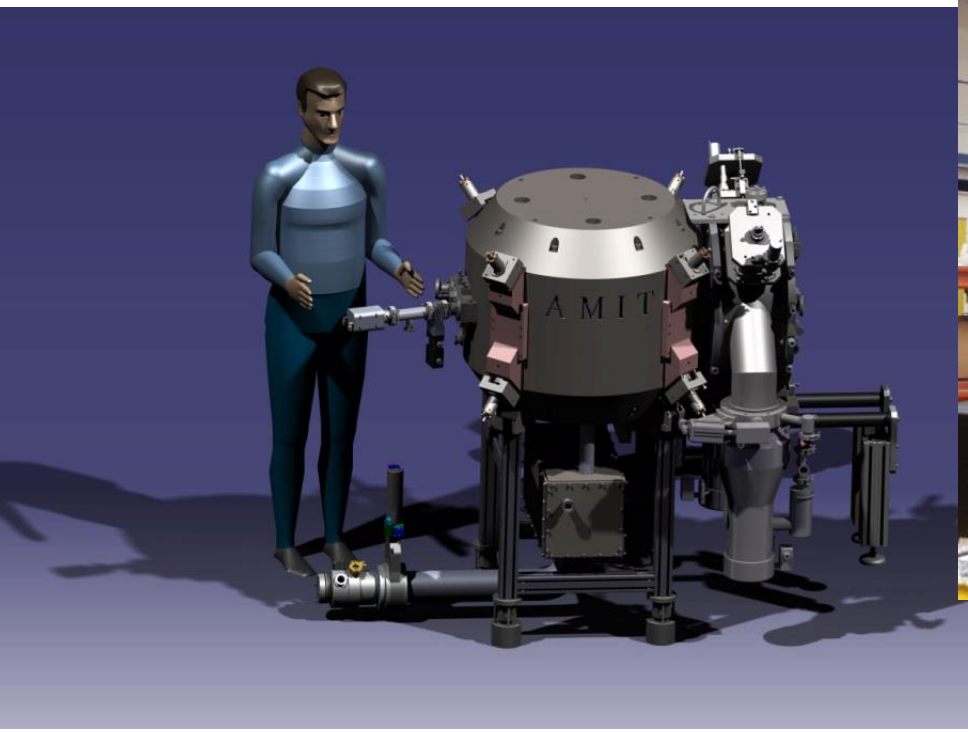
Developments to tackle issues

- Compact cyclotrons for patient-sized doses in hospitals
- For ^{18}F (2 hrs), but also ^{11}C (20 mins) and ^{15}O (2 mins)
- AMIT (CIEMAT, Spain, plus collaborators)



4T magnet, based on CERN work
>8.5 MeV, >10 μA
Tests soon

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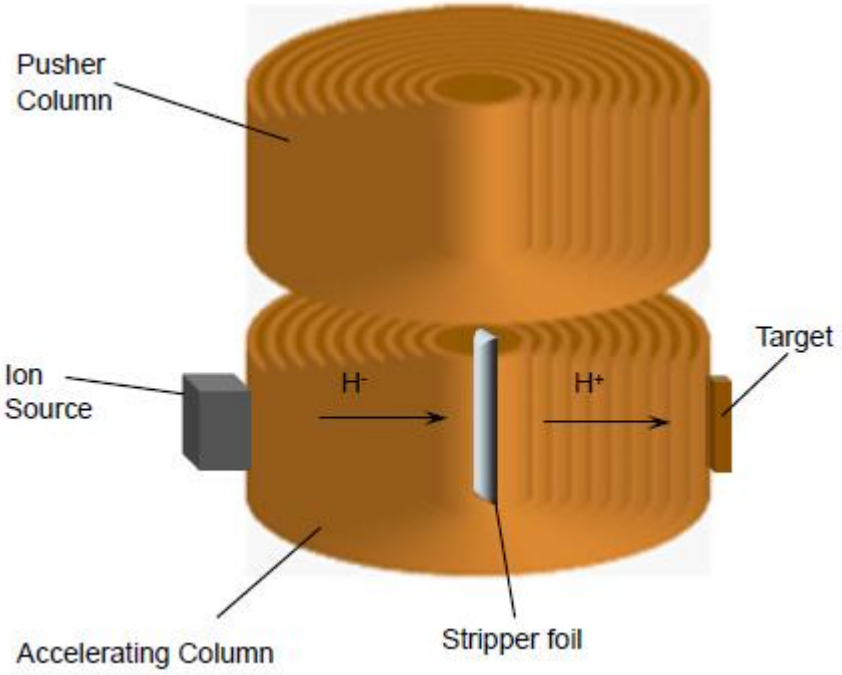
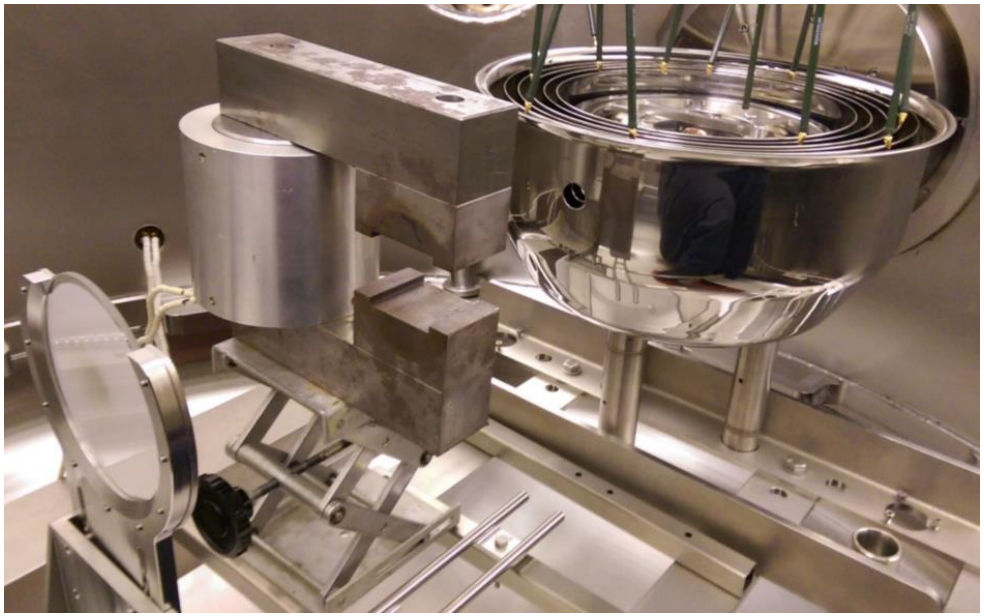
Developments to tackle issues

- Compact tandem electrostatic accelerator: The Oniac (Siemens)
- Aim: 10 MeV, ~2 mA



Courtesy: Siemens



Tested to >100 μA

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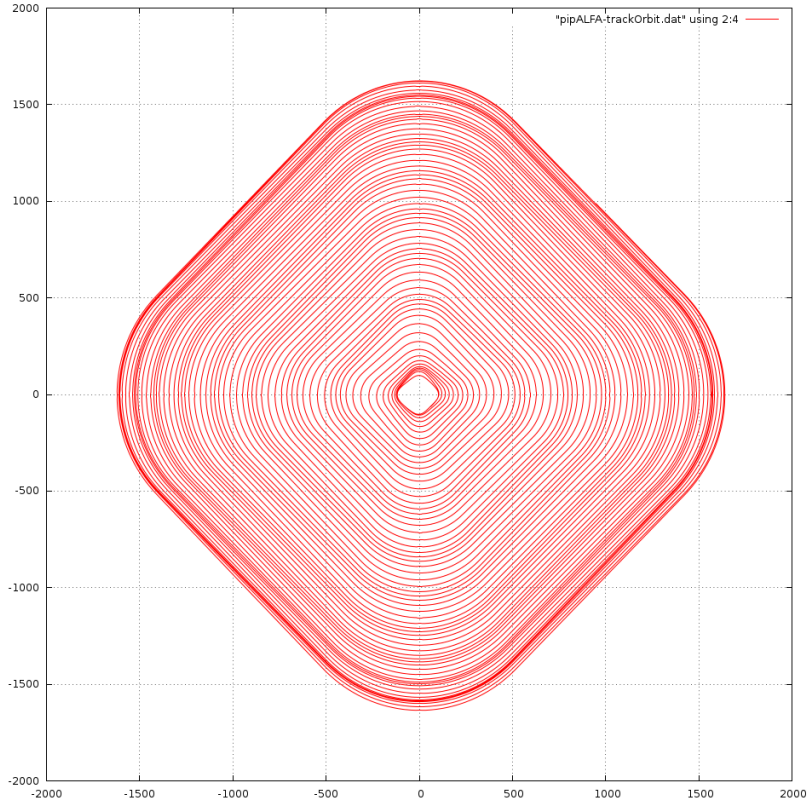
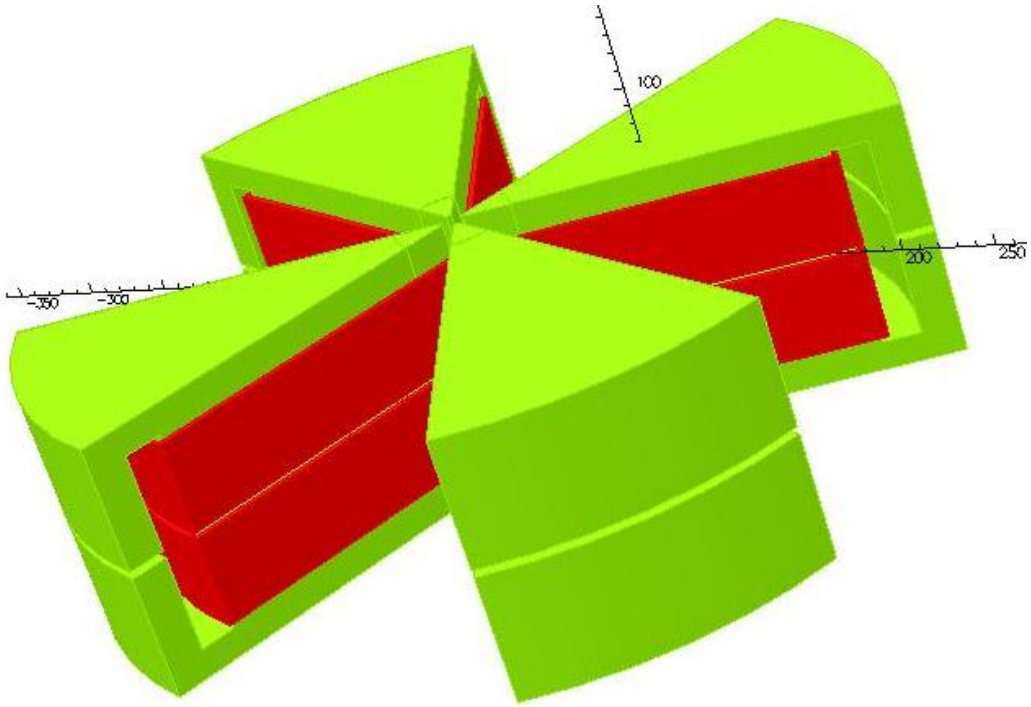
Developments to tackle issues

- Non-scaling FFAG (PIP)
- Aim: 0.075 to 28 MeV, ~20 mA protons and a
- Possibility of internal target





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Radioisotopes Conclusions

- There may or may not be a moly problem!
- Existing and new PET isotopes have a lot of potential
- Therapeutic isotopes are a mess:
  - they have a lot of potential
  - supply can be a problem
  - accelerators can help, but are somewhat limited by current technology
- Several technologies being developed

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Industrial Applications

- Ion implantation
- Ion beam analysis
- Electron beams for industrial applications
- Electron beams for environmental applications

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Industrial Applications

- **Ion implantation:** **an energetic process by which impurity atoms are introduced into the *near surface* of a material to change its *electrical, optical or materials* properties:**
  - **Doping in semiconductors**
  - **Device isolation in integrated circuits**
  - **Compound synthesis**
  - **Defect Engineering**
  - **Waveguides and optical devices**
  - **Anti-fouling**
  - **Wear resistance in metals - hip replacement**
- **Beam energy: typically 10 to 500 keV, but up to 5 MeV**
- **Beam current: 10 μA to 30 mA**
- **Electrostatic accelerators**
- **>10000 in operation**

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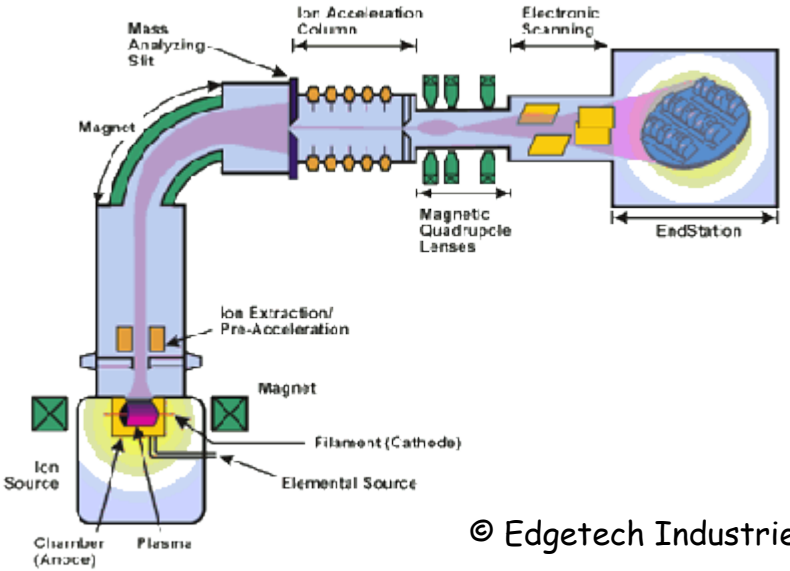
Ion Implantation



© Edgetech Industries

© Applied Materials

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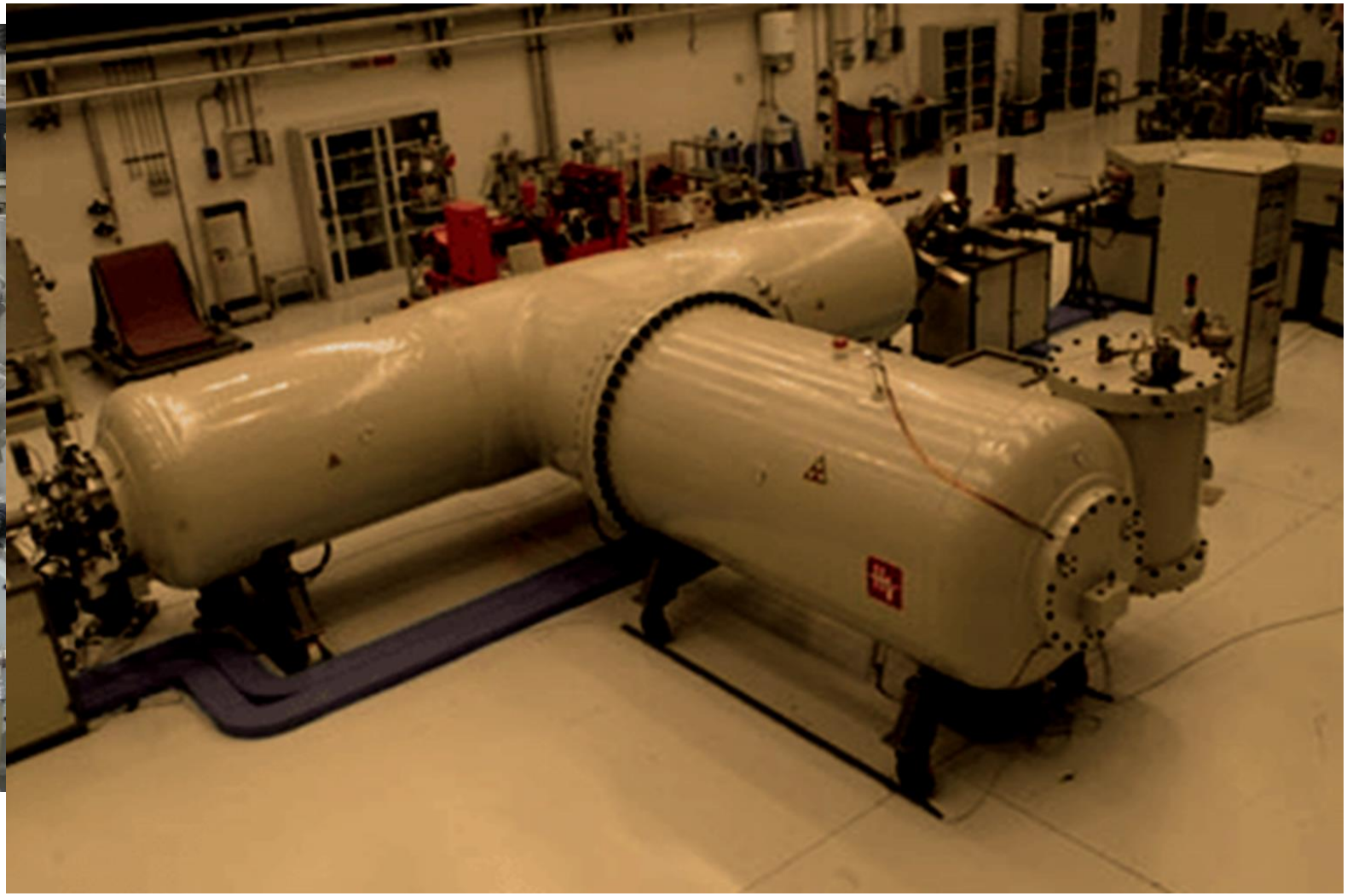
Ion Beam Analysis

Ion beam analysis: determining material structure and composition
>1500



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Ion Beam Analysis

Variety of techniques:

- Accelerator Mass Spectrometry (AMS)
- Particle Induced X-ray Emission (PIXE)
- Rutherford Back Scattering (RBS)
- Elastic Recoil Detection Analysis (ERD)
- Particle Induced Gamma ray Emission (PIGE)
- Nuclear Resonance Reaction Analysis (NRA)
- Charged Particle Activation Analysis (CPA)

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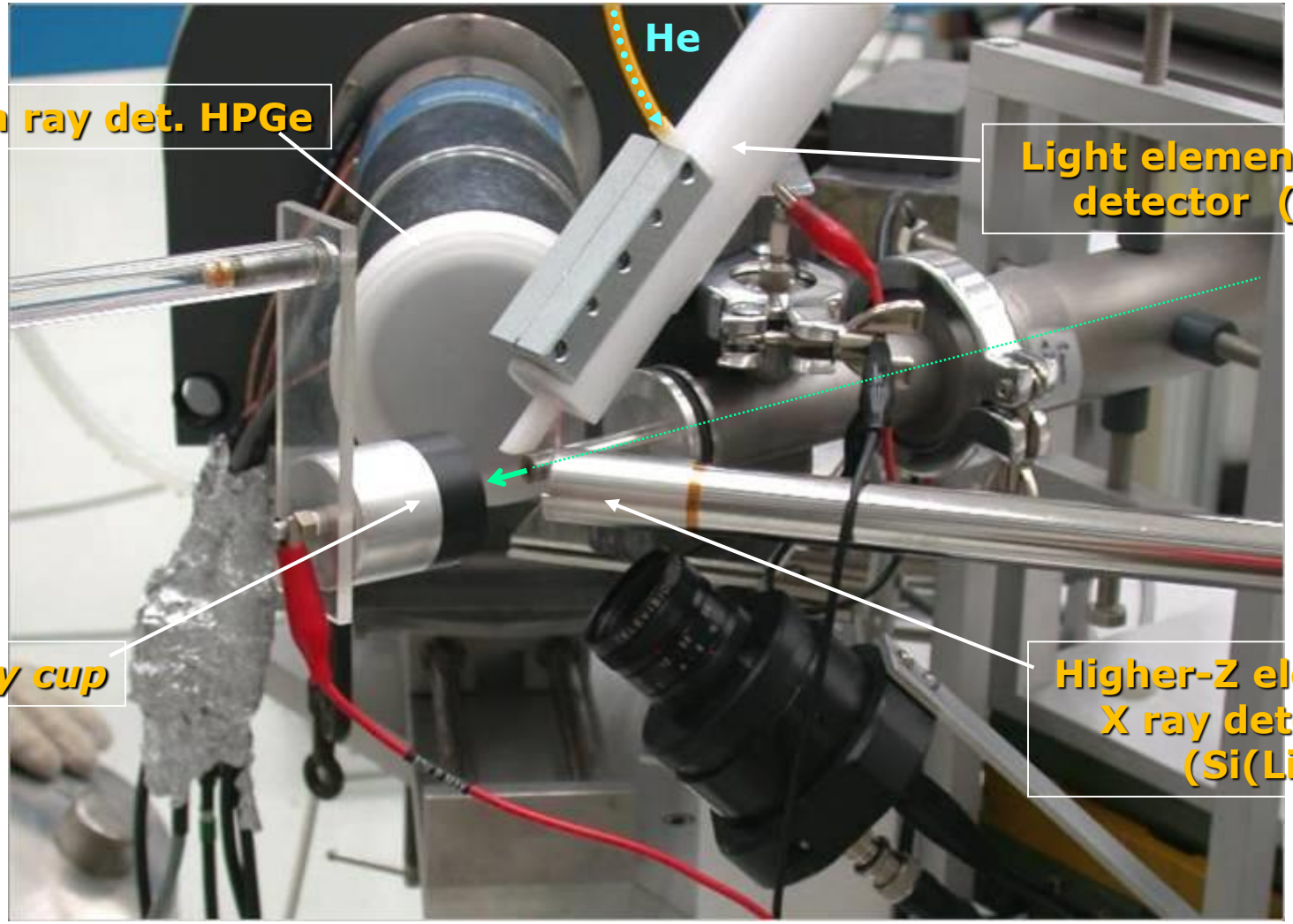
IBA



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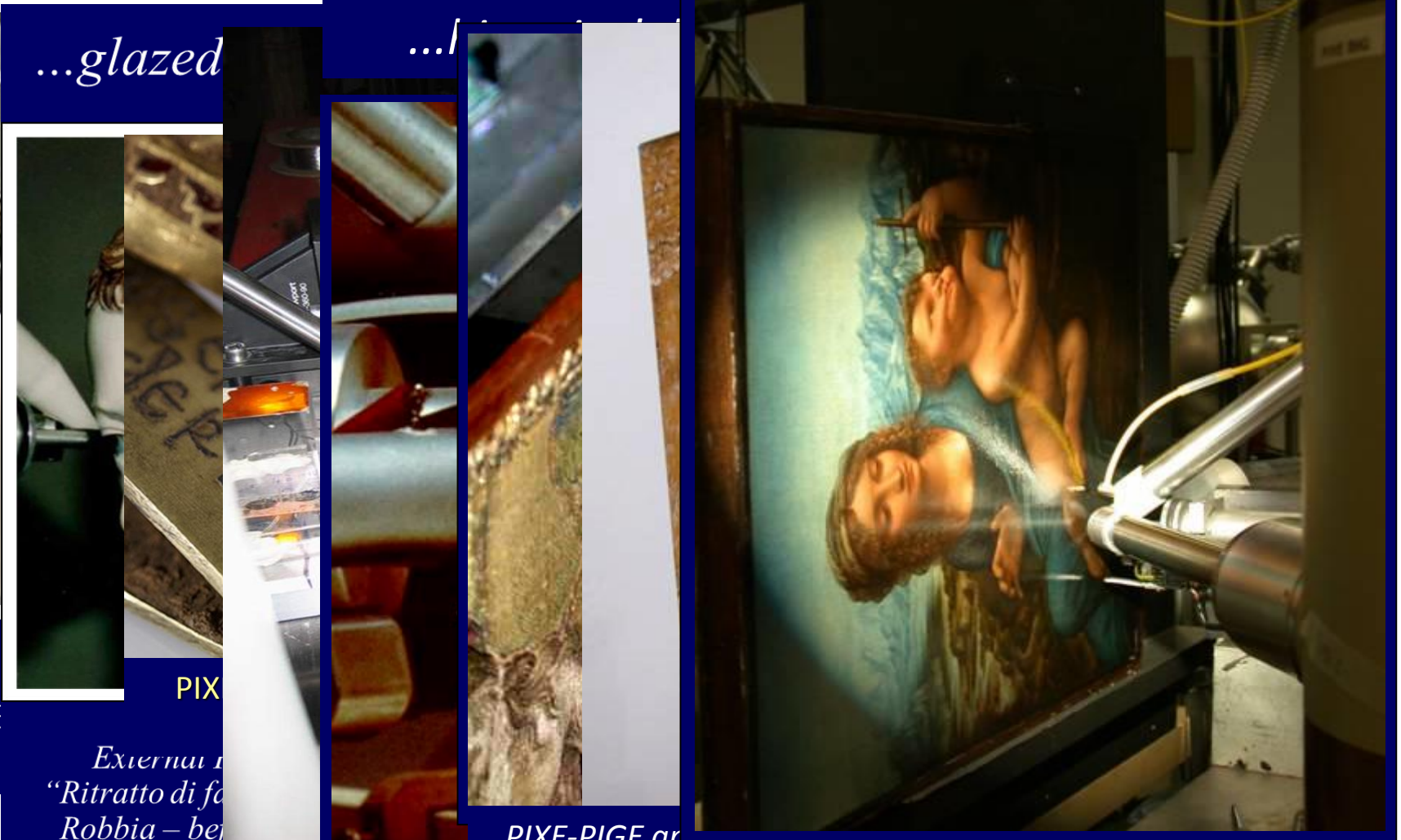

...glazed

PIX

Differential PIXE and PIGE analysis of the Madonna dei Fusi by Leonardo

Raffaellino del Garbo

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Electron Beams

- Many applications
- Tend to be classed as
  - very low energy: 10 to 300 keV
  - low energy: 300 keV to 10 MeV
- Above 10 MeV causes activation
- Overlap in applications

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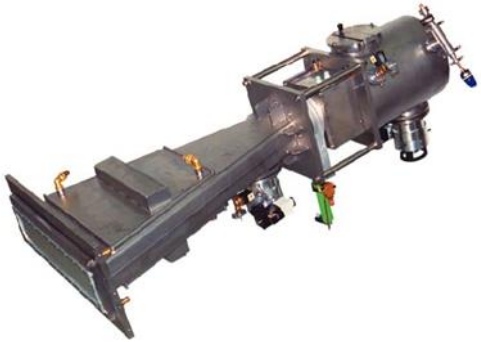
Low Energy Electron Beams

>10000 accelerators:

< 5 MeV ~ electrostatic, mainly industrial applications

5 – 10 MeV ~ RF linacs for security (& medical)
~ rhodatron for high currents for industry



300 keV Electron Crosslinking

1 MeV for water treatment

10 MeV IBA Rhodotron

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Very Low Energy Electrons

Effects of Electron Beam Interaction

Thermal Processes	Non-thermal Processes	
Heat Production	Chemical Reactions	Biocidal Effects
Vacuum	Atmosphere	Atmosphere
- Evaporation - Melting - Welding / Joining - Hardening - Micro- structuring	- Curing - Crosslinking - Drying print-inks - Surface modification (Grafting)	- Disinfection of animal feed - Seed treatment - Sterilisation of products - Sterile packaging - Inactivation of pharma waste

Courtesy Frank-Holm Roegner

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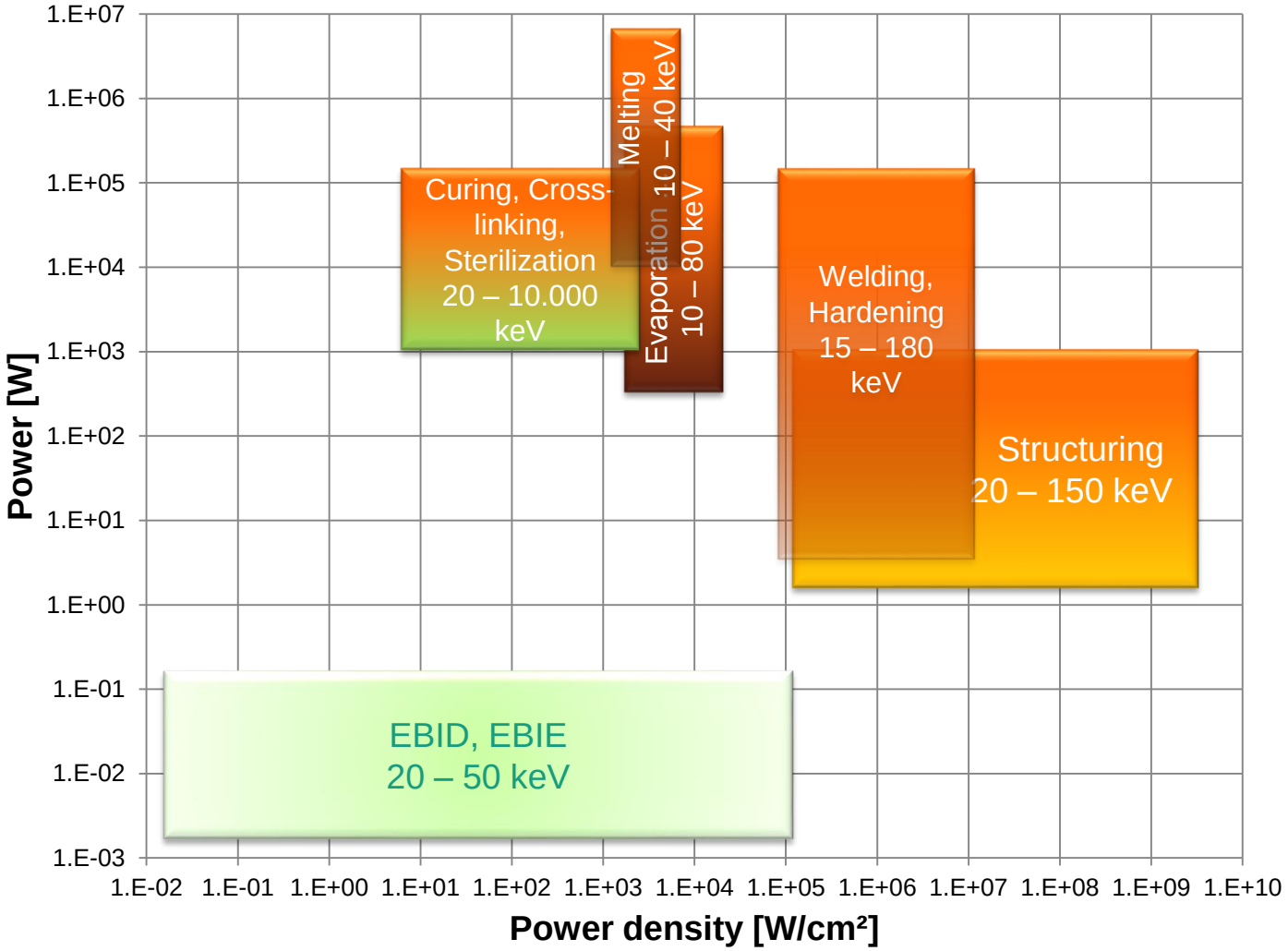
Very Low Energy Electrons



Courtesy Frank-Holm Roegner

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Very Low Energy Electrons

Sterilisation of bottles
Example: Hitachi Zosen Corp., Japan

Before filling the ready formed 500 ml PET bottles are sterilized by being irradiated from both the inside and outside using AEB - low-energy electron beams 150 keV (outside), and 100-125 keV (inside). Process time 2-4 seconds per bottle, with 25 kGy dosis.

Standard production lines for filling 500-ml PET bottles at a rate of 600 bottles per minute.

Courtesy Frank-Holm Roegner

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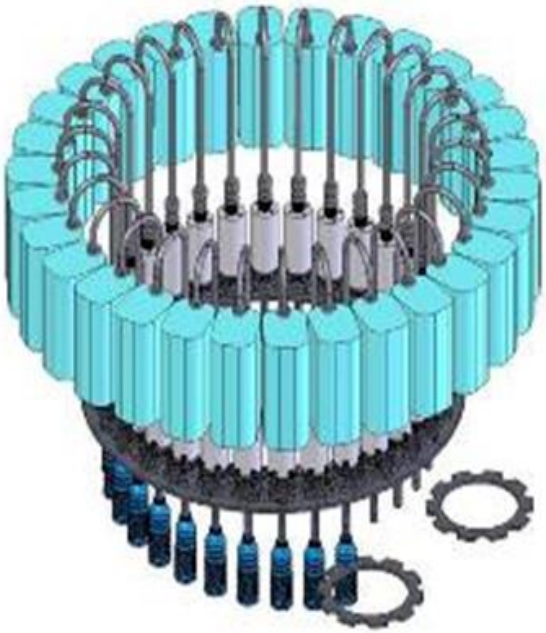
Very Low Energy Electrons

Sterilisation of bottles
Example: Hitachi Zosen Corp., Japan

Sterilization by electron beam irradiation
(illustration of device interior)

Filling with beverage



Courtesy Frank-Holm Roegner

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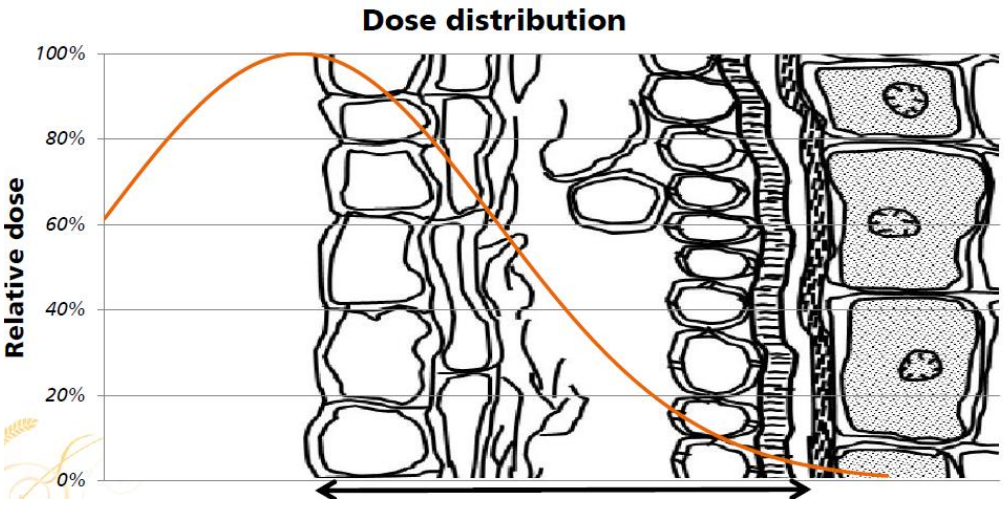
Very Low Energy Electrons

Treatment of seeds
Example: Frauenhofer FEP



Courtesy Andre Weidauer

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Very Low Energy Electrons

Curing of lacquer on furniture
Example: Scannery Holztechnik GmbH, Falkenhagen/Germany

Continuous transportation of furniture sheets

Courtesy Frank-Holm Roegner

Lacquered wood floor for industrial use

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Very Low Energy Electrons

Curing of lacquer on furniture
Example: Scannery Holztechnik GmbH, Falkenhagen/Germany

Courtesy Frank-Holm Roegner

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Low Energy Electrons

Market segment	Typical energy	Electron penetration
Surface curing	80 – 300 keV	0.4 mm
Shrink film	300-800 keV	2 mm
Wire & Cable	0.4 – 3 MeV	11 mm
Sterilization	4 – 10 MeV	38 mm
Food	4 – 10 MeV	38 mm
Composites (carbon fiber)	10 MeV	24 mm or less
Flue gas	300 – 1000keV	120cm to 3m
Wastewater	1MeV	2mm
Biological sludge	1 – 10 MeV	2mm do 30mm

Courtesy Andrzej Chmielewski

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Low Energy Electrons

Application	Dose range
Medical – diagnostic	10 – 100 mGy
Medical – therapy	1 – 10 Gy
Industrial – food and agriculture	0.1 – 10 kGy, or more
Industrial - sterilization	10 – 30 kGy
Industrial – materials modification	50 – 100 kGy, or more
Flue gas treatment (SOx, NOx,VOC)	2-10 kGy
Wastewater	1 to 2 kGy
Biological sludge	2 to 3 kGy

Courtesy Andrzej Chmielewski

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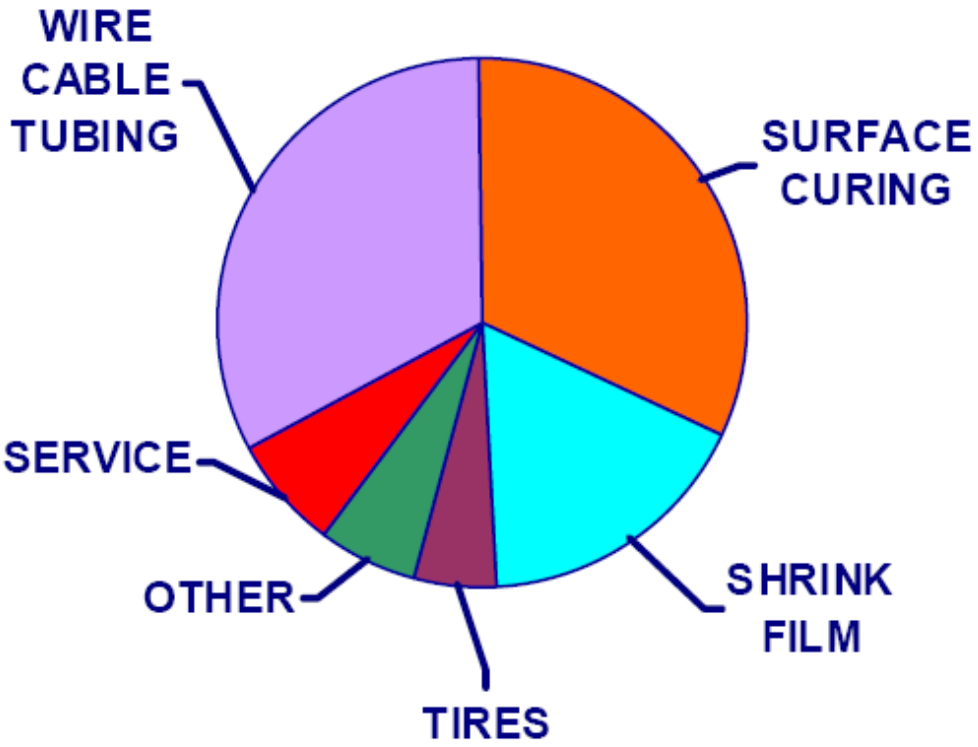
Low Energy Electrons



Courtesy Andrzej Chmielewski

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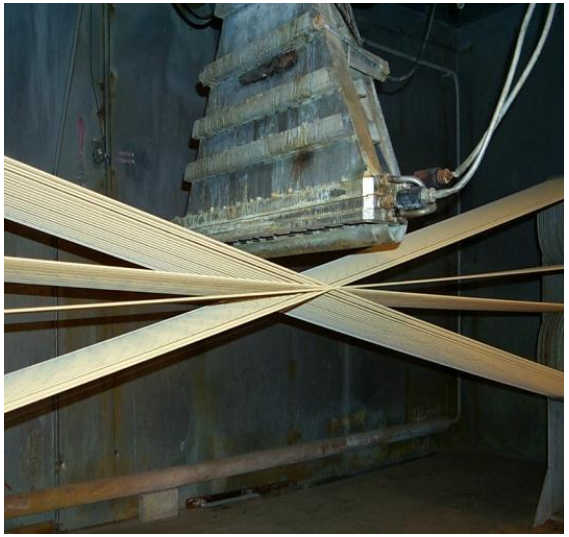
Low Energy Electrons



Courtesy Grazyna Przybytniak

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Low Energy Electrons

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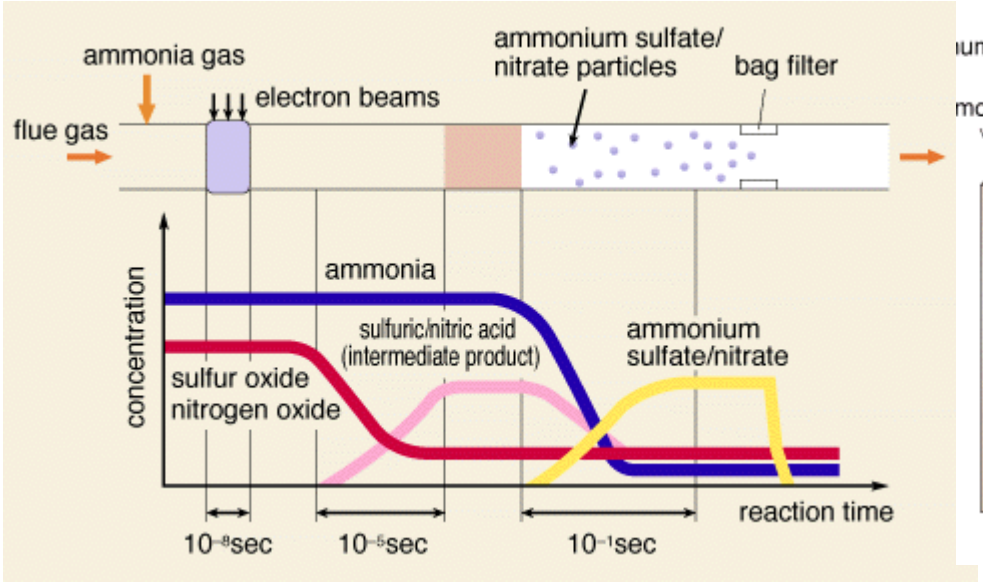
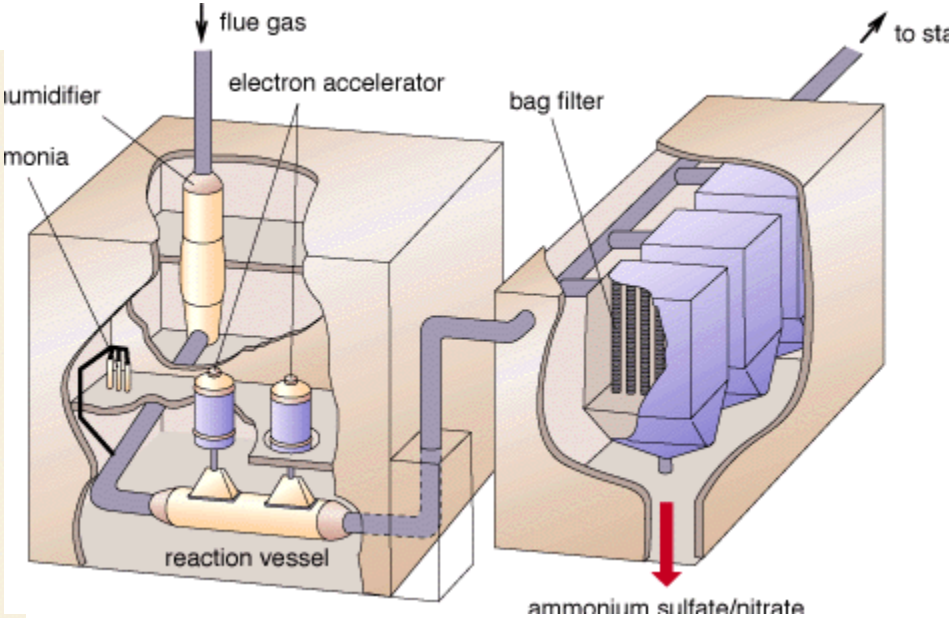
Flue Gas Treatment

- Removal of NOx, SOx and VOC
  - Avoid acid rain
- Current technique:
  - chemical
  - bi-product is gypsum
- Electron beam technique:





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Flue Gas Treatment

~4 pilot plants
Not used in production yet

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Cargo Ships

- Removal of NOx and SOx from diesel engines
- Treatment of ballast water transported around the world

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Water Treatment

- Currently, 1.9B people use either an unimproved water source or an improved water source that is faecally contaminated
- In Africa, it is estimated that 15-20% of deaths are water related
- First two targets of the United Nations Sustainable Development Goal 6:
  - 6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all
  - 6.2: By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations
- Can accelerators help?

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Water Treatment

- Basic process:
  - e^- react with water to produce active radicals:
    OH^*, H^*, H_2O_2
  - radicals react with contaminants to remove in various ways
  - very similar to cancer therapy!
- Already used industrially:
  - Wastewater from Textile Dyeing Companies
  - Wastewater from Papermill
  - Leachate from Sanitary Landfill
  - Wastewater containing Heavy metals (Cd,Hg,Pb,Cr^{+6})
  - Re-use of effluent from sewage plant
  - Remediation of contaminated water (PCB,Explosives)
  - Contaminated Underground water
  - Drinking water

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Water Treatment

Wastewater Treatment Facility in Daegu Dyeing Industrial Complex

Courtesy: B.Han

120 companies, 80000m^3 of waste water per day

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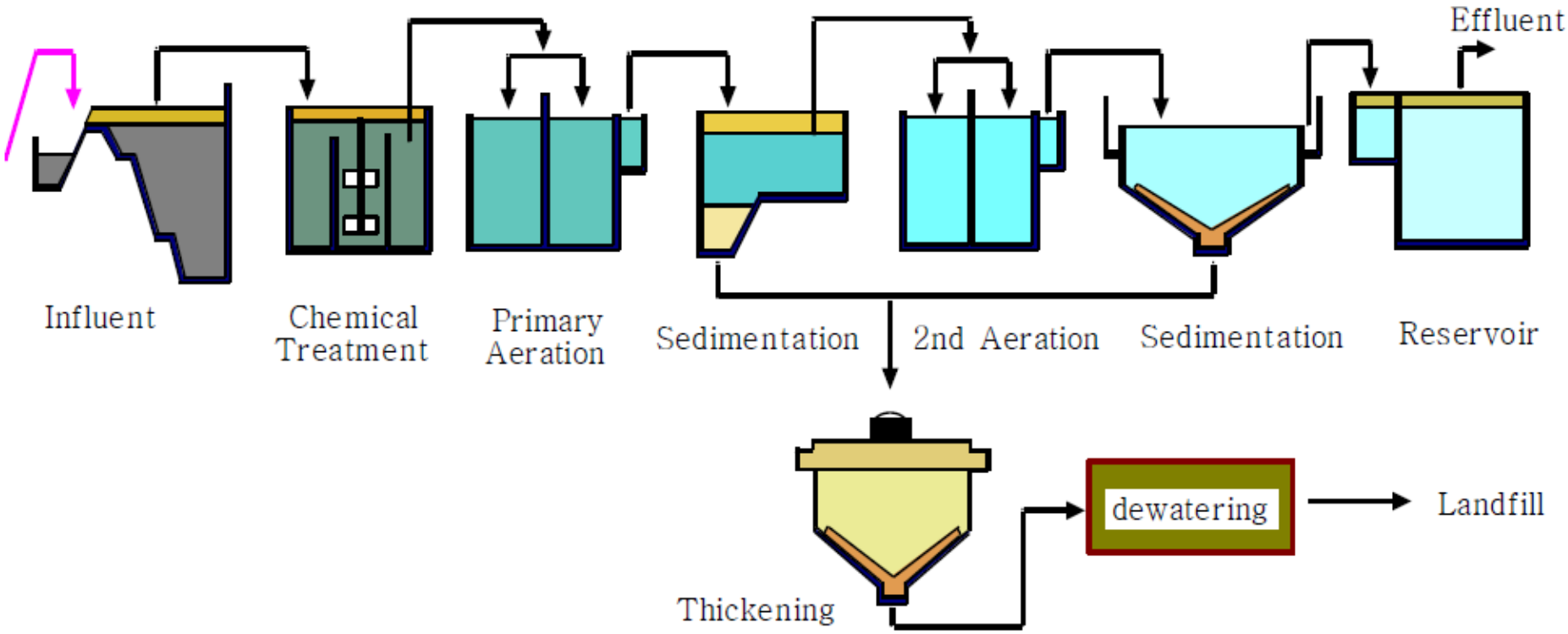
Water Treatment



Process Flow of Existing Wastewater Treatment Facility

Courtesy: B.Han

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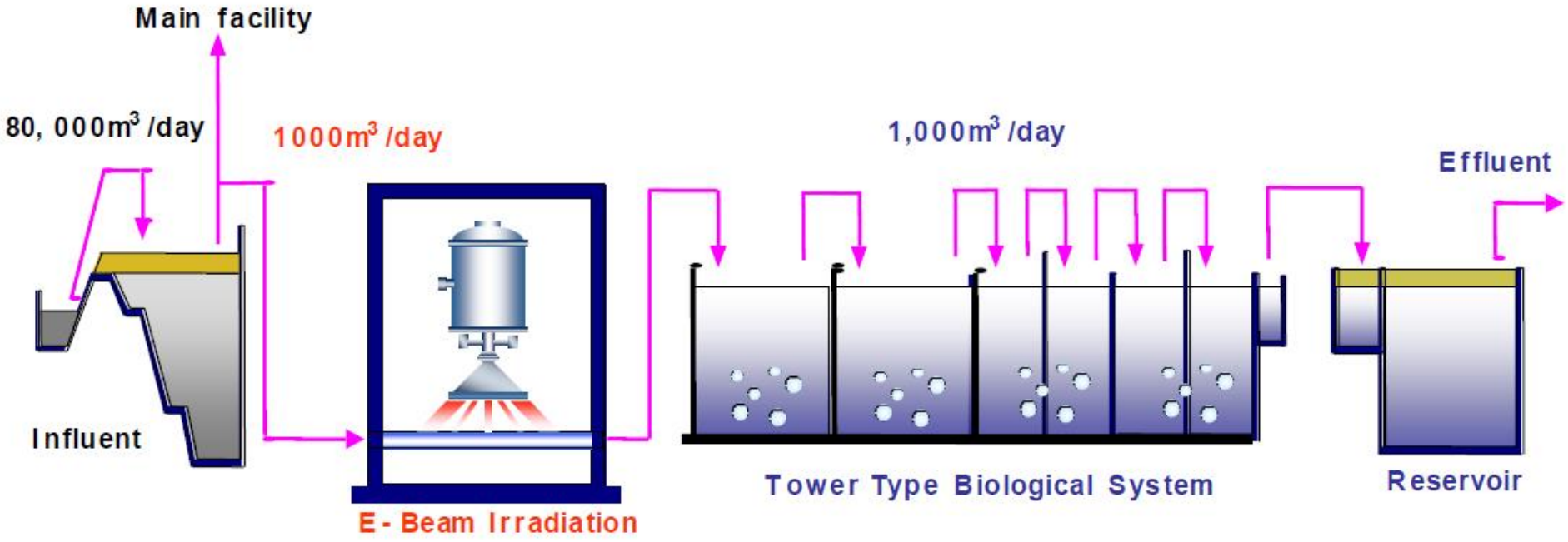
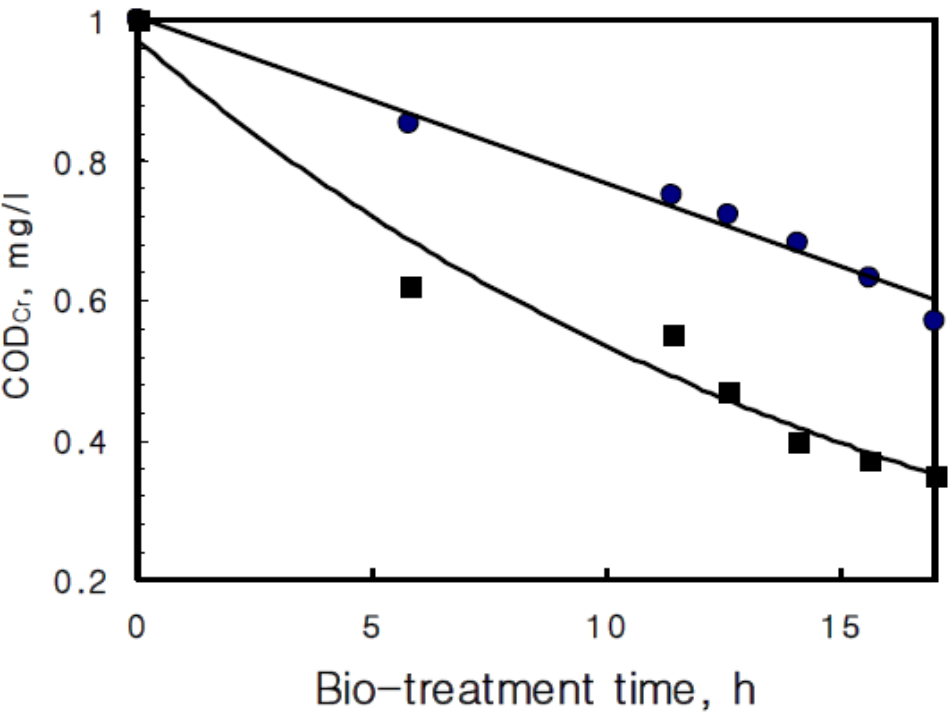
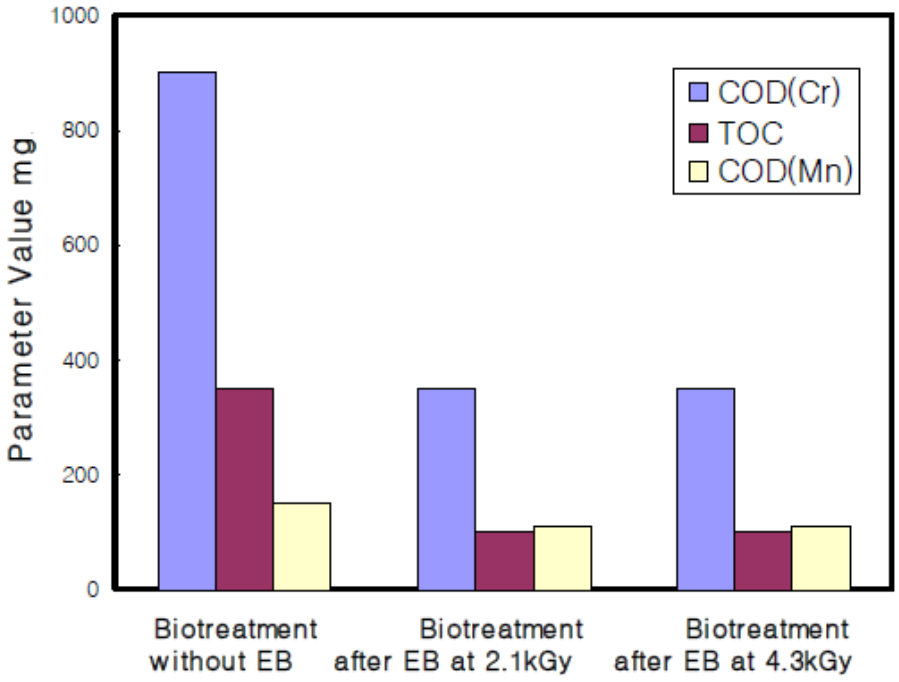
Water Treatment



Courtesy: B.Han

Water Treatment





Effect of electron-beam treatment on biological treatment of dyeing wastewater:
a - kinetics of biotreatment of irradiated (*1*) and unirradiated (*2*) wastewater;
b - absorbed dose effect on combined electron-beam/biological treatment.

Courtesy: B.Han

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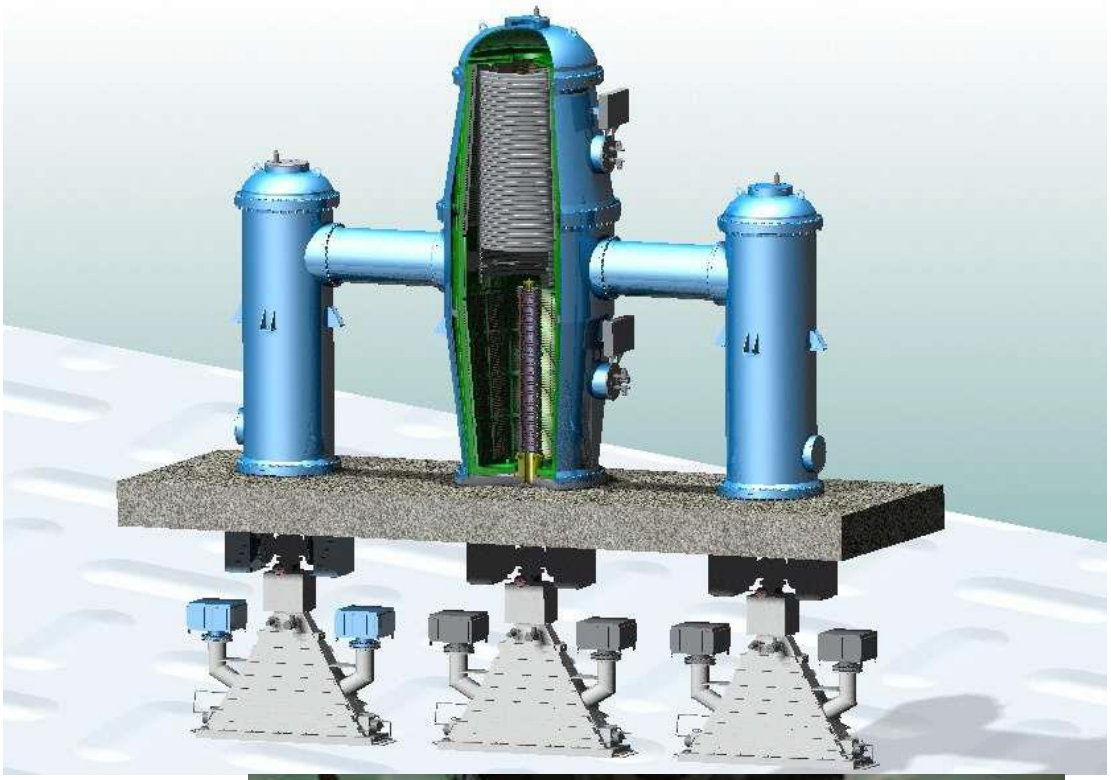
Water Treatment

Commercial plant

10000m^3/day

1 MeV, 400 kW



Courtesy: B.Han

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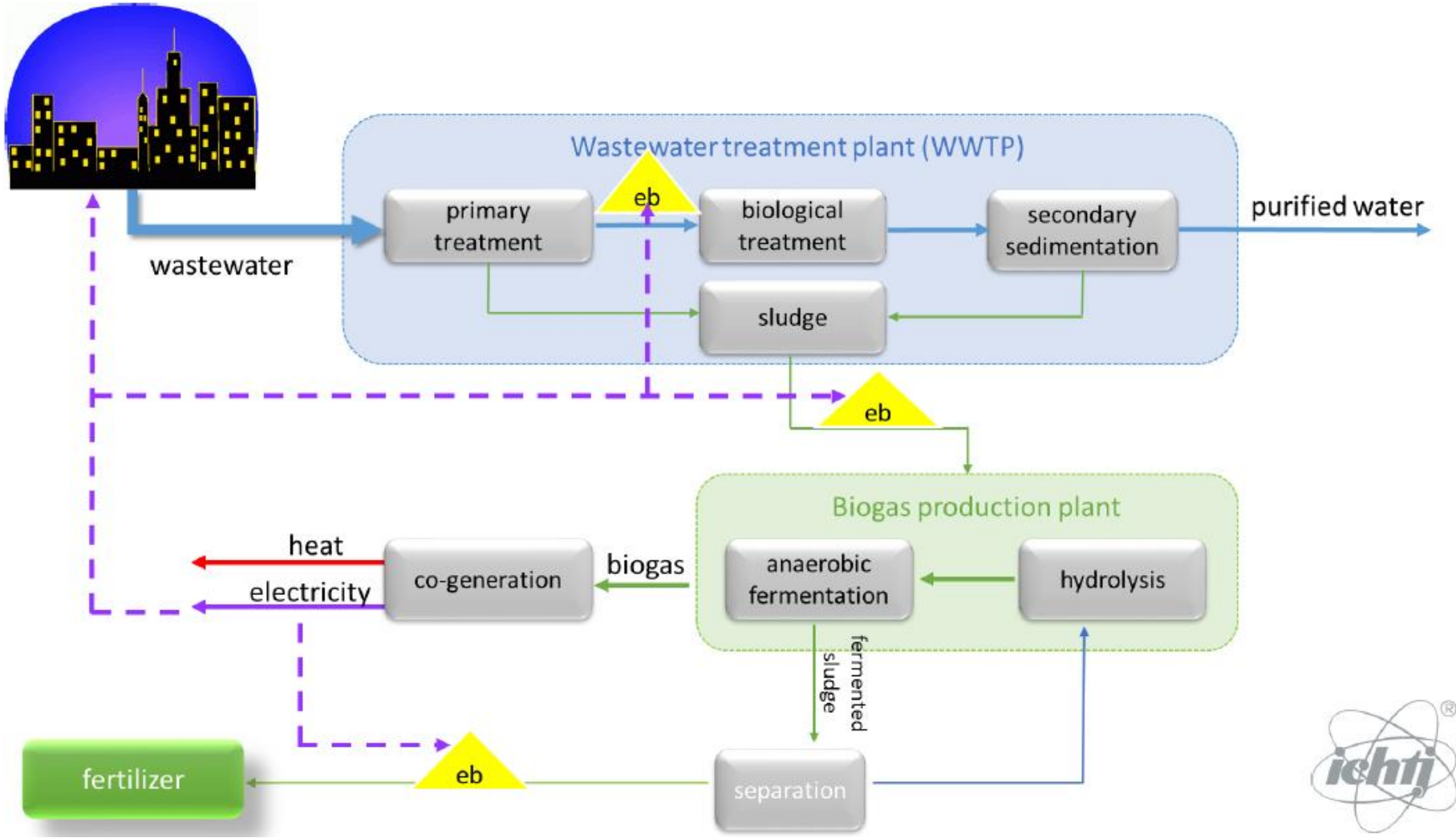
Biological Sludge Treatment

- Called many things: what's left over after waste water treatment
- Highly contaminated:
  - difficult to deal with everywhere
  - major cause of sickness and death in developing world
- Developed disposal old:
  - dumped at sea
  - discharged in surface water
- Now:
  - anaerobic digestion → fertiliser
  - incineration (some times for power production)
  - landfill

Biological Sludge Treatment



Courtesy: Urszula Gryczka

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Biological Sludge Treatment

- Environmentally friendly
- Disposal of problematic waste
- Bio-gas production
  - 60% more efficient
  - smaller facility
  - faster
- Production of microbiologically safe organic fertiliser
- Technology can be used anywhere with sufficient biomass, no need for external power
- Pilot plant under development in Poland
- Proposal submitted for studies in Ghana and Uganda

Courtesy: Urszula Gryczka

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Industrial Conclusions

- Industrial applications are very important……
- ……but not very glamourous!
- Environmental applications:
  - have a lot of potential
  - but need to be cost-effective
  - big companies need to be convinced of the benefits
- For the developing world:
  - lots of potential
  - main focus needs to be on developing simple, cheap systems
  - must meet in the local needs
  - outreach is just as important

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General Conclusions

- Accelerators are v. important for things other than making Higgses
- They are already used extensively
- But new applications are still being developed
- Technology for research can and is playing a role
- But the requirements are different
- Technology needs to be adapted to meet the needs
- Not vice versa