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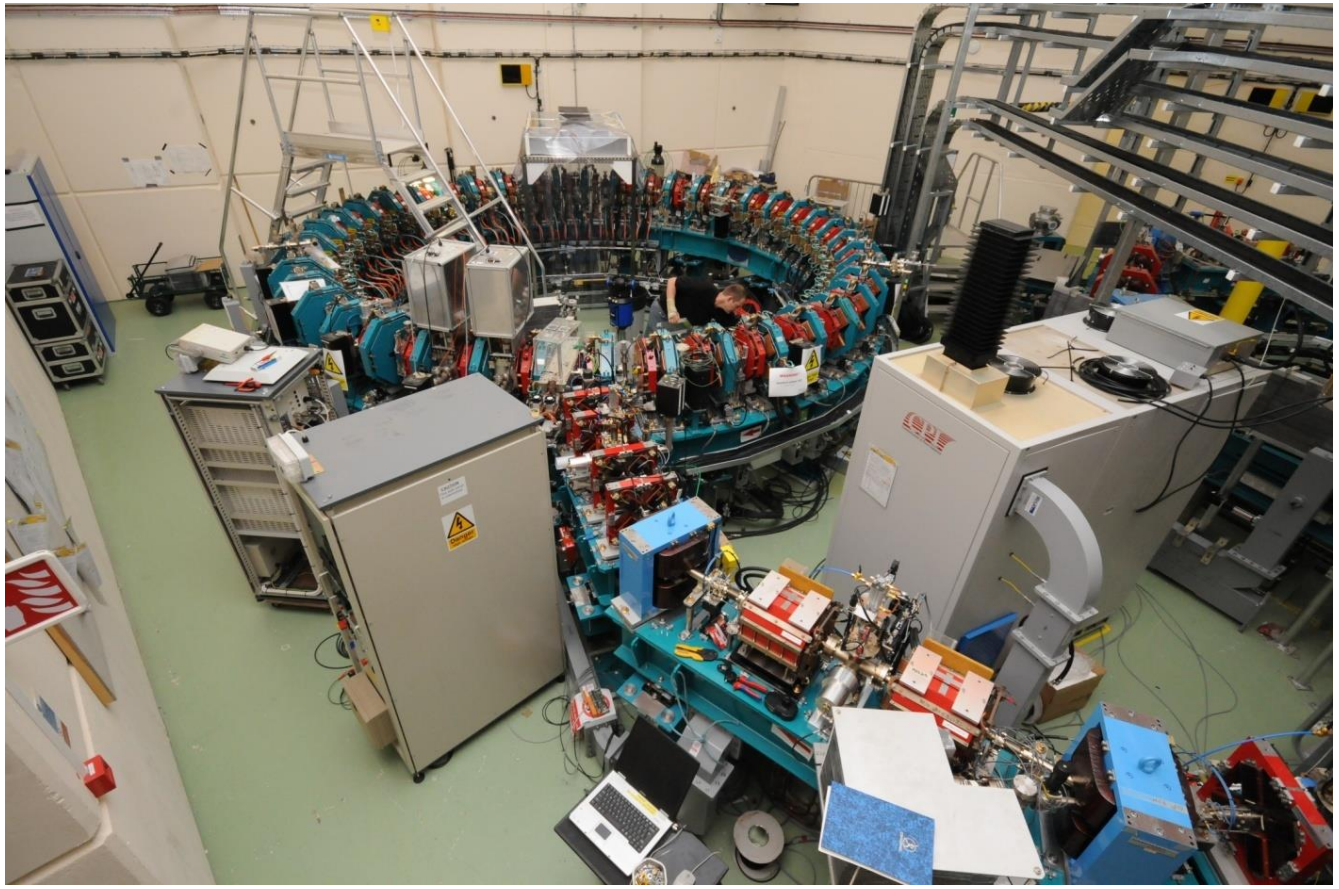
Applications of Accelerators

Prof Rob Edgecock
Rutherford Appleton Laboratory and
University of Huddersfield



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Outline

- Summary of accelerator applications outside research
- Industrial applications of electron beams
- Environmental applications of electron beams
  - poo
  - diesel engine exhaust gases
- Industrial applications of ion beams
  - ion implantation
- Medical applications
  - cancer therapy

Introduction

- Nearly 40000 accelerators in the World
- About half < 5 MeV
- Nearly all the rest < 20 MeV
- About 2/3rd electrons, 1/3rd ions
- Used for a variety of every day applications:

- Energy	- few, developing
- Environment	- few, developing
- Medical	- >15000
- Industry	- >21000
- Security	- ~1000

- Most of the accelerators: commercially manufactured
- Produce around $0.5T of commerce/year

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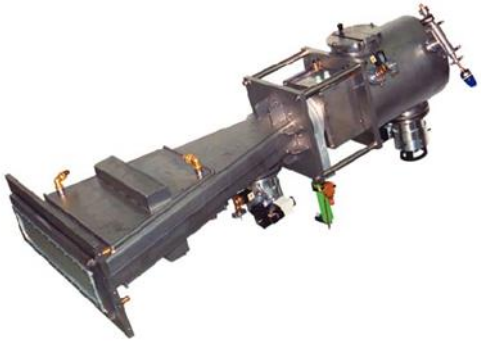
Electron Industrial Applications

>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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Electron Industrial Applications

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

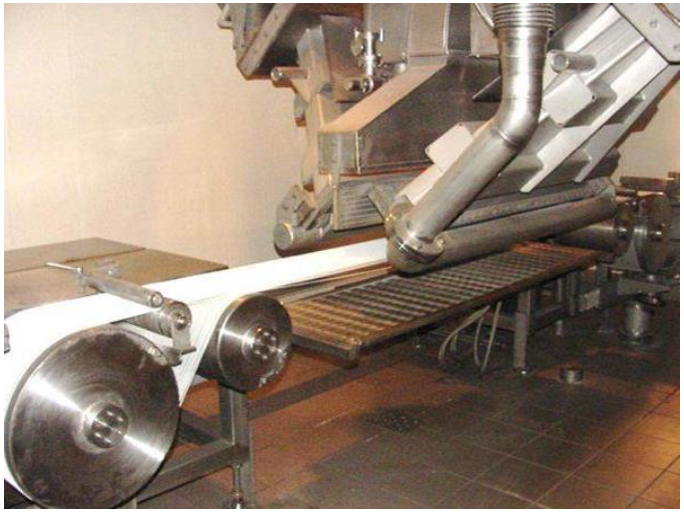
Polymer Cross-linking

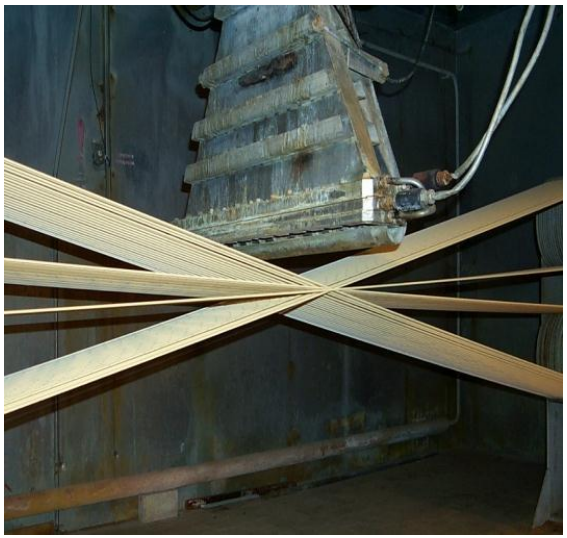
92% radial tyres

Nearly all wires/cables

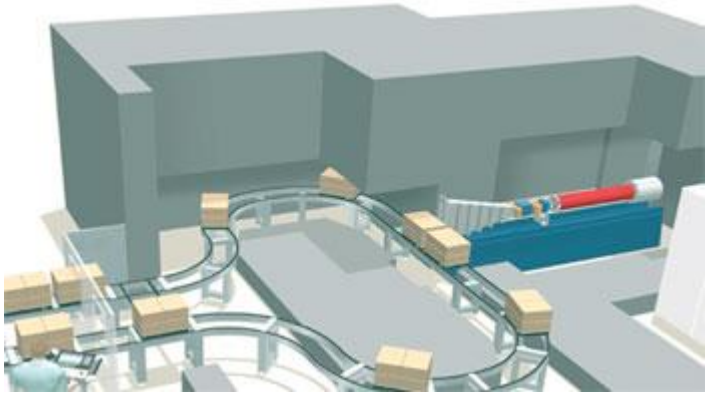
Most foam

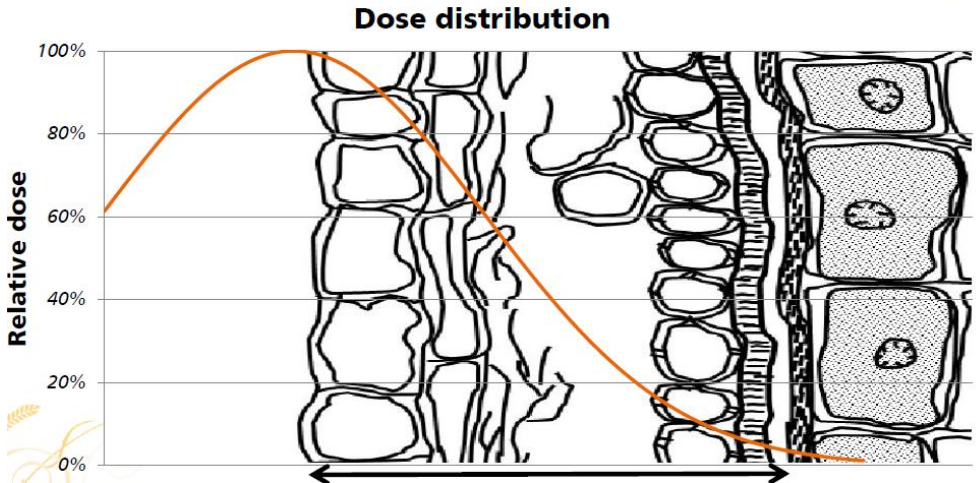
Polymer Cross-linking





Sterilisation





Gemstone enhancement

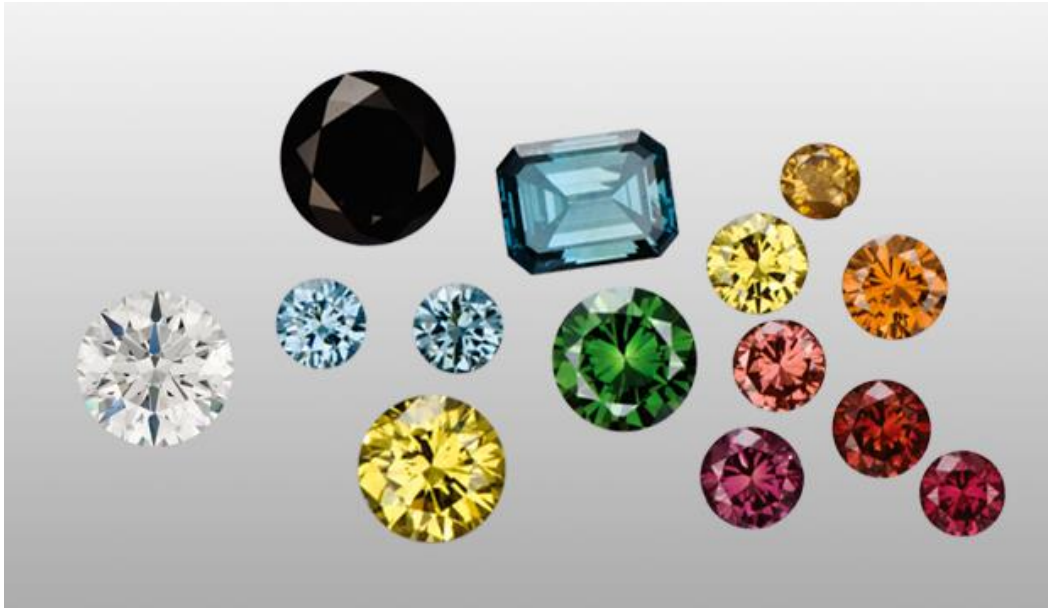
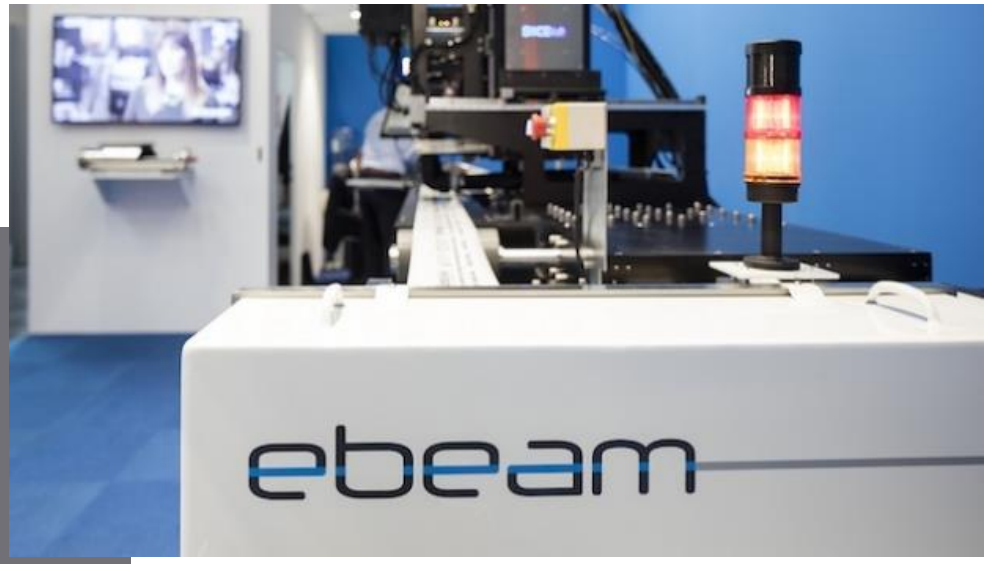


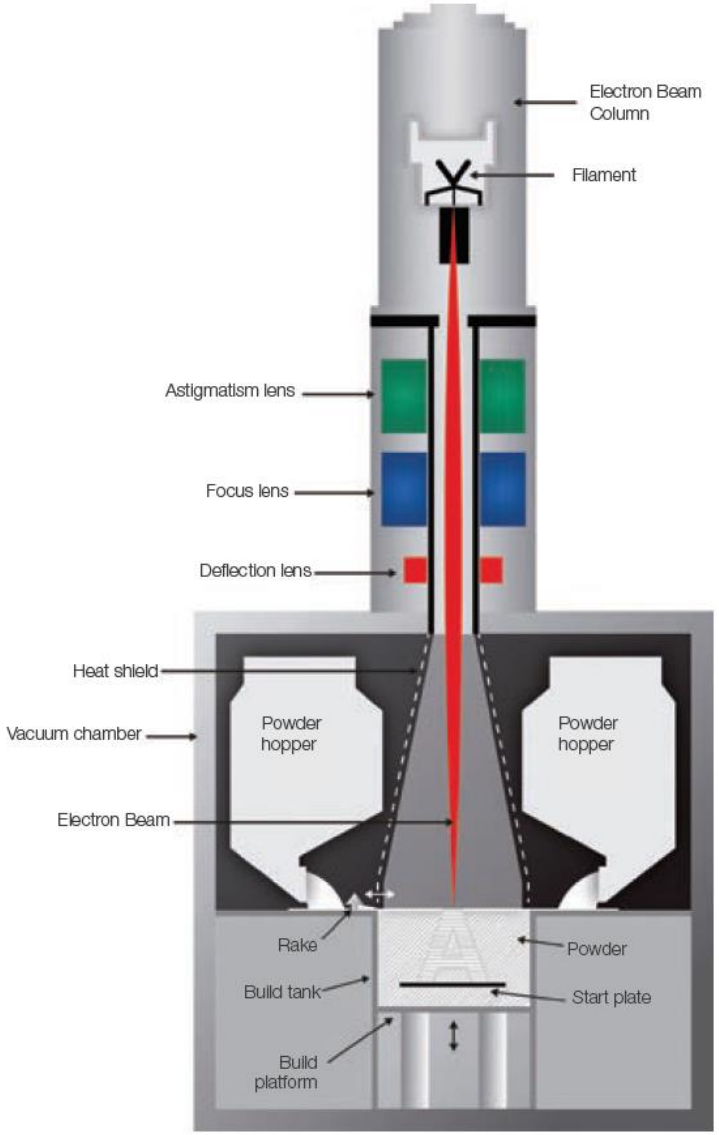
TABLE 2. Effects of irradiation treatment on various gem materials.[a]

Material	Starting color	Ending color
Beryl	Colorless	Yellow
	Blue	Green
Maxixe-type	Pale or colorless	Blue
Corundum	Colorless	Yellow
	Pink	Padparadscha
Diamond	Colorless or pale to yellow and brown	Green or blue (with heating, turns yellow, orange, brown, pink, red)
Fluorite	Colorless	Various colors
Pearl	Light colors	Gray, brown, "blue," "black"
Quartz	Colorless to yellow or pale green	Brown, amethyst, "smoky," rose
Scapolite[b]	Colorless, "straw," pink, or light blue	Blue, lavender, amethyst, red
Spodumene	Colorless to pink	Orange, yellow, green, pink[c]
Topaz	Yellow, orange	Intensify colors
	Colorless, pale blue	Brown, blue (may require heat to turn blue), green
Tourmaline	Colorless to pale colors	Yellow, brown, pink, red, bicolor green-red
	Blue	Purple
Zircon	Colorless	Brown to red

2D printing



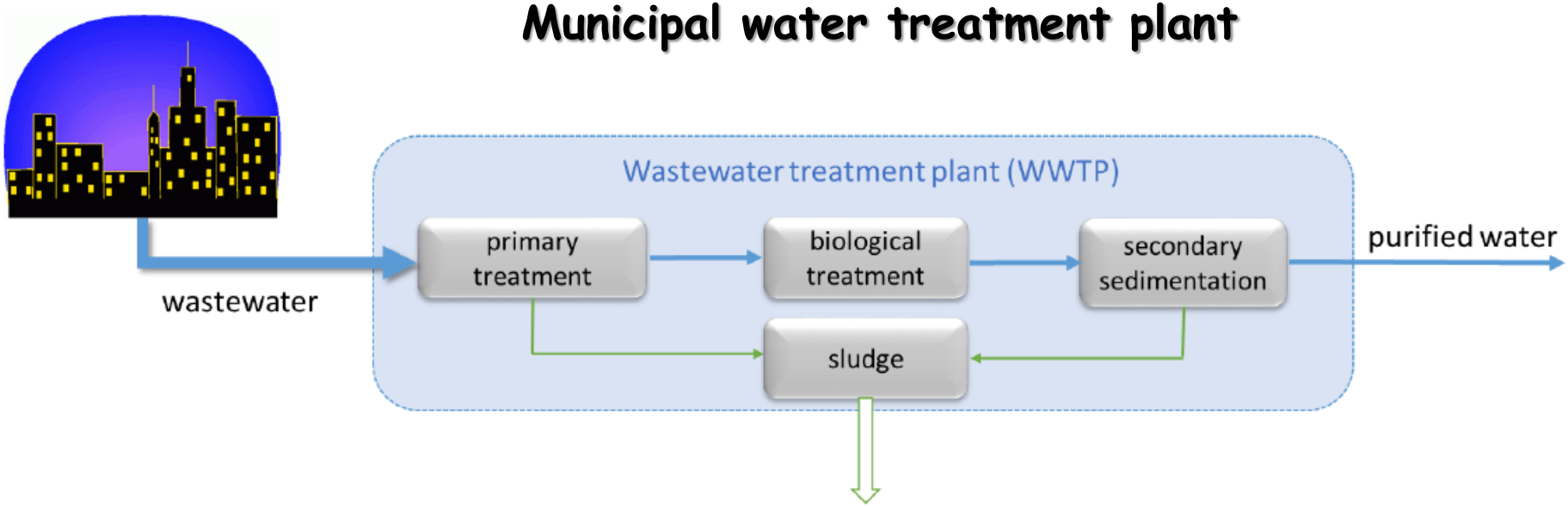
3D printing or additive manufacturing



Arcam EBM® systems, schematic architecture.

Environmental Applications

Municipal water treatment plant



- Biological sludge: highly contaminated – bacteria, viruses, parasite eggs, etc
- Developed world: difficult to dispose of
- Developing world: major source of ill-health and death

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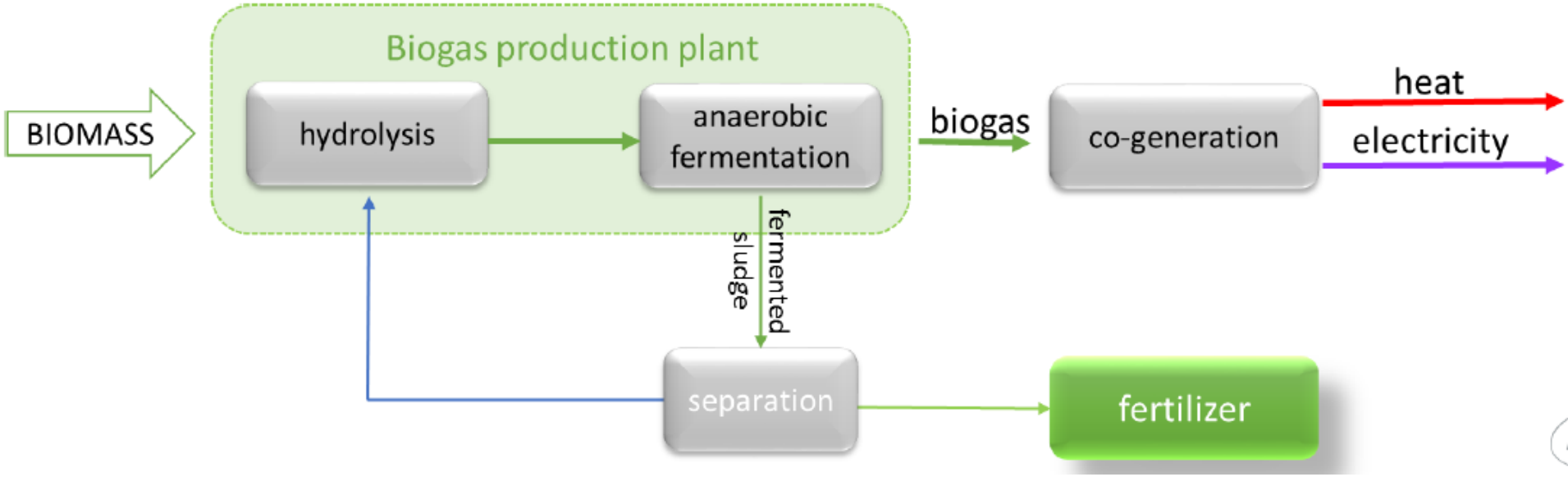
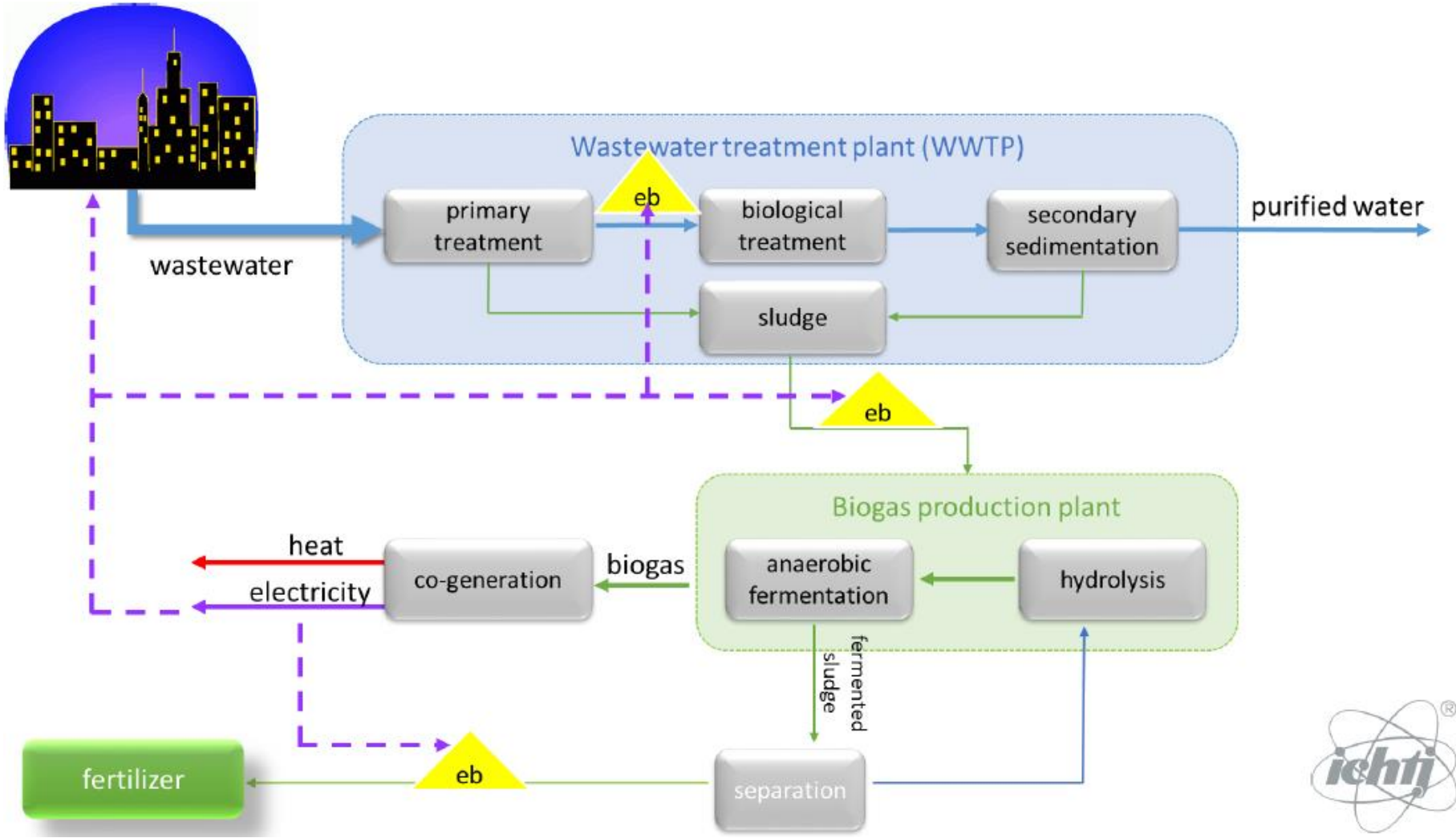
Anaerobic Digestion



- Anaerobic digestion: micro-organisms break down organic matter
- Typically runs at 35-39°C, takes around 20 days
- Outputs
  - biogas
  - cleanish fertilizer
  - 50% less organic material

Biological Sludge Treatment



Courtesy: Urszula Gryczka

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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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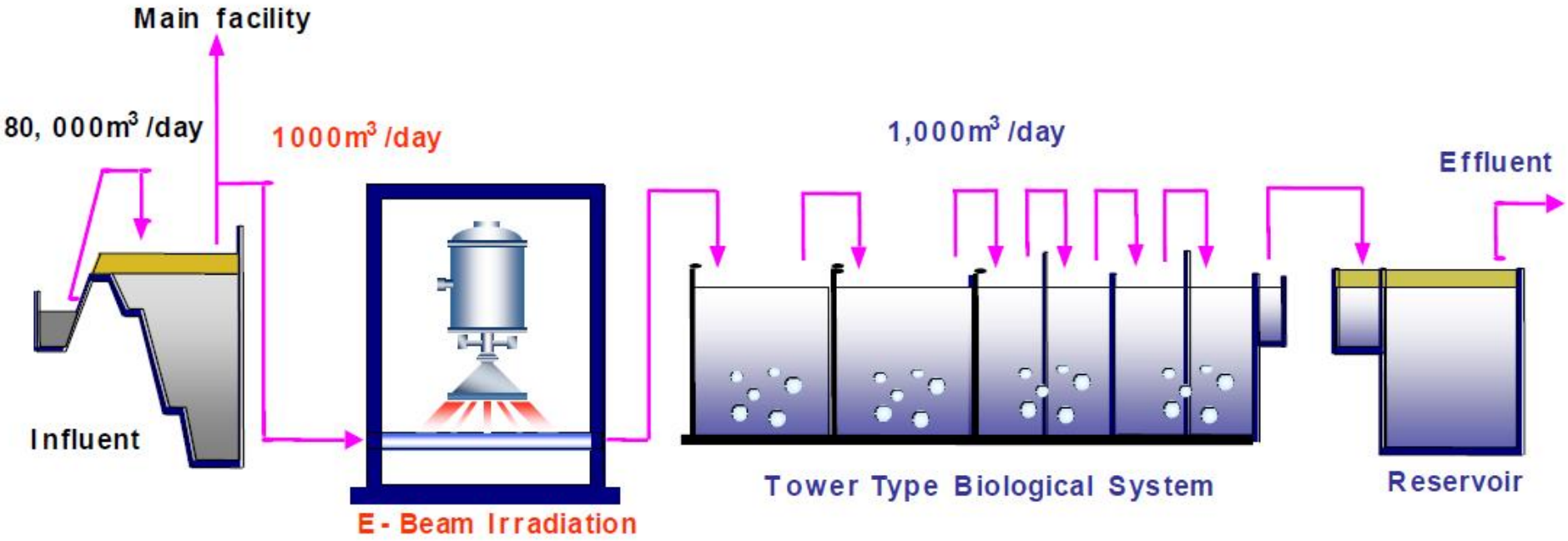
Water Treatment



Courtesy: B.Han

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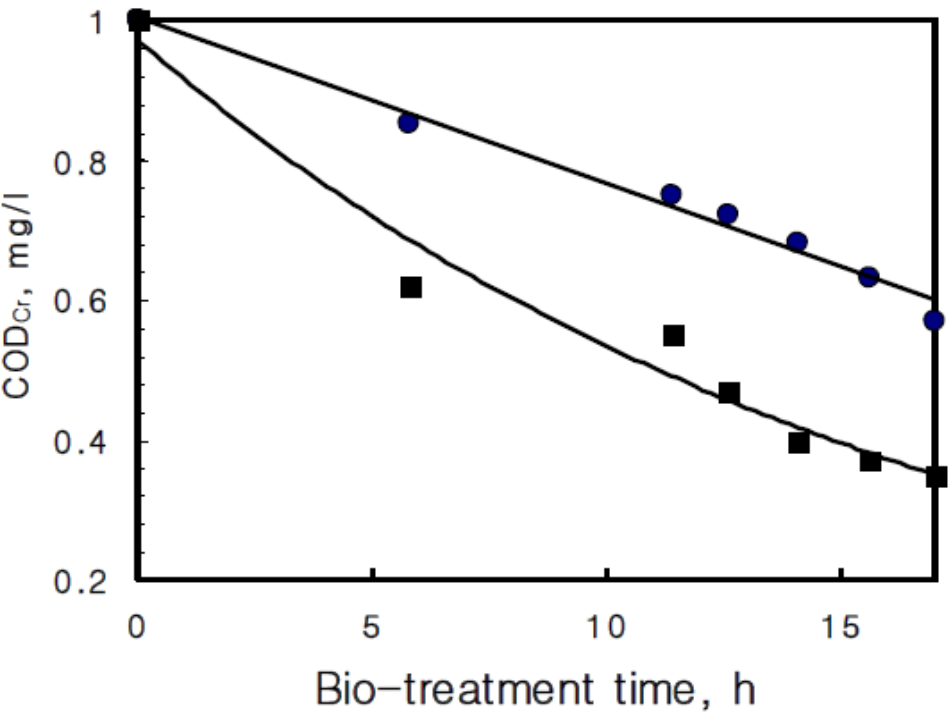
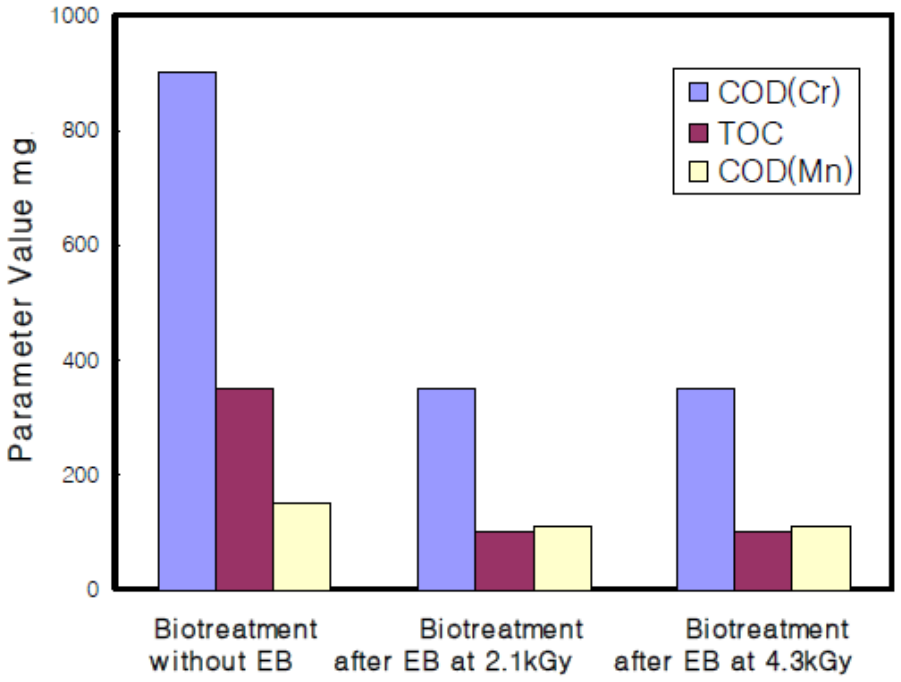
Water Treatment





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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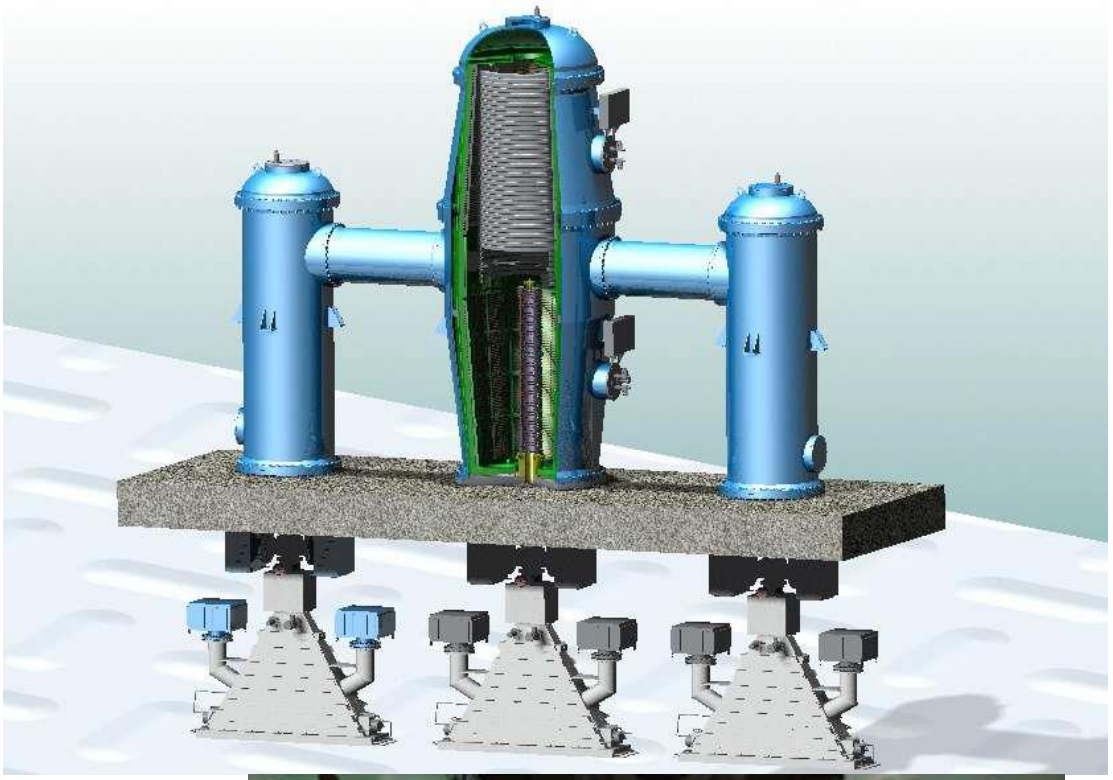
Water Treatment

Commercial plant

10000m^3/day

1 MeV, 400 kW



Courtesy: B.Han

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Biological Sludge Treatment

- Kills >99.9% of pathogens
- Breaks down longer organic molecules
- Bio-gas production
  - 60% more efficient
  - faster
  - smaller facility required
- 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

Courtesy: Urszula Gryczka

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Biological Sludge Treatment

Participation in the design and start-up of biogas plants with capacity of 1.2 MW in Koczergi and Międzyrzec etc.

Courtesy: Urszula Gryczka

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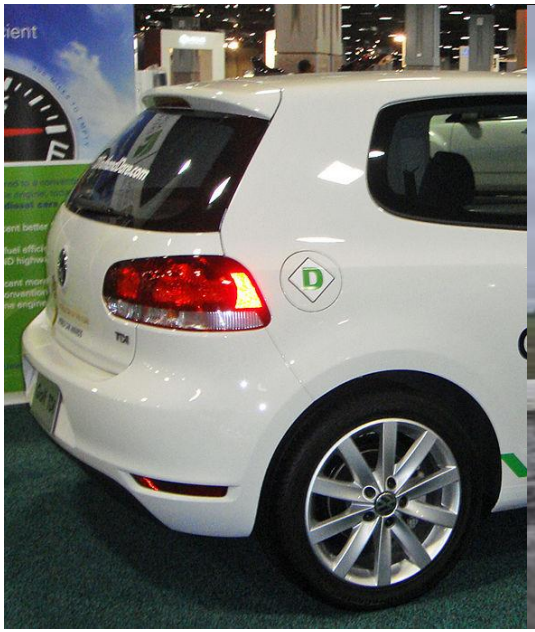
Diesel Exhaust Gas Treatment

- Diesel engine exhaust gases:
  - "particulates"
  - SO_2
  - NO
  - NO_2
  - VOC
- Controls in place (at some level) for



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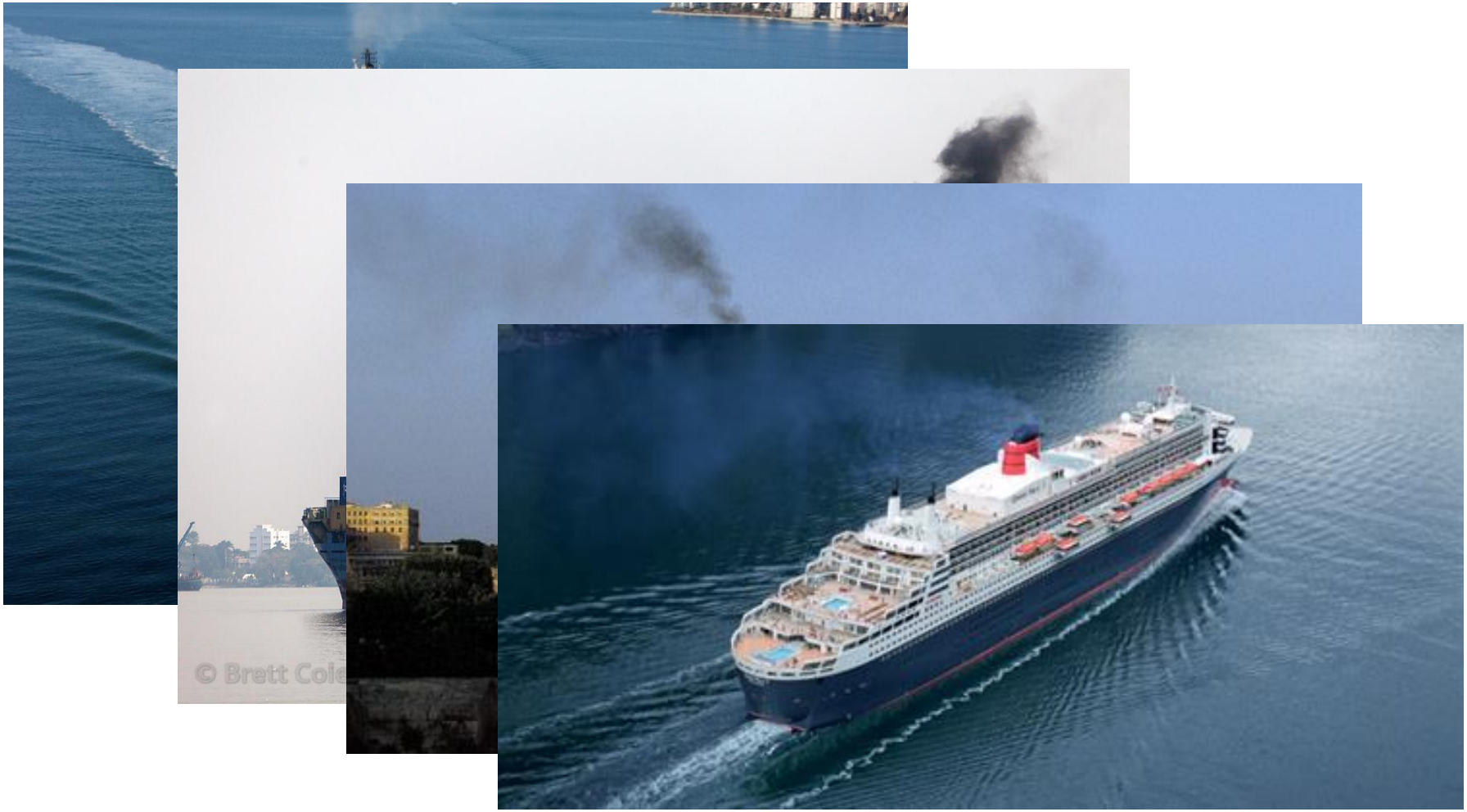
Diesel Exhaust Gas Treatment



Larger ships: 80-100 MW diesel engines
134 kHP

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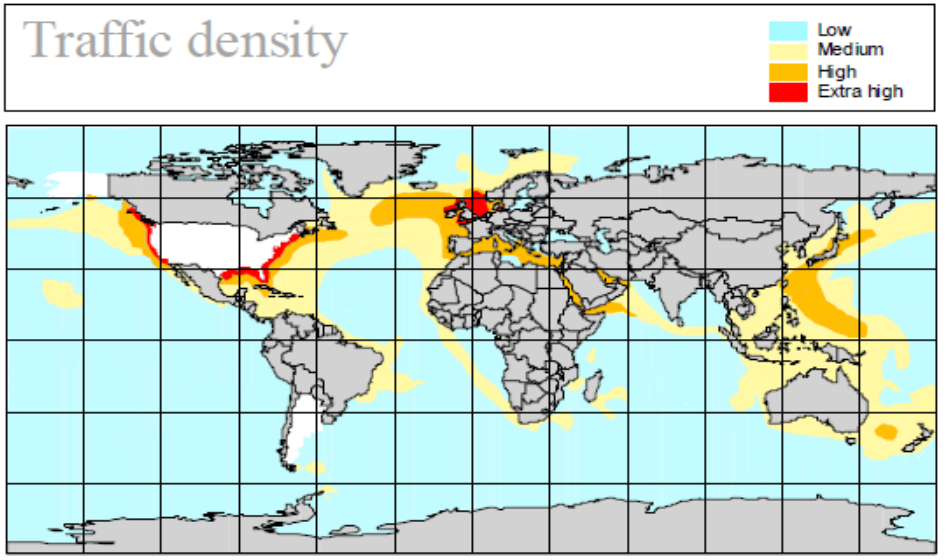
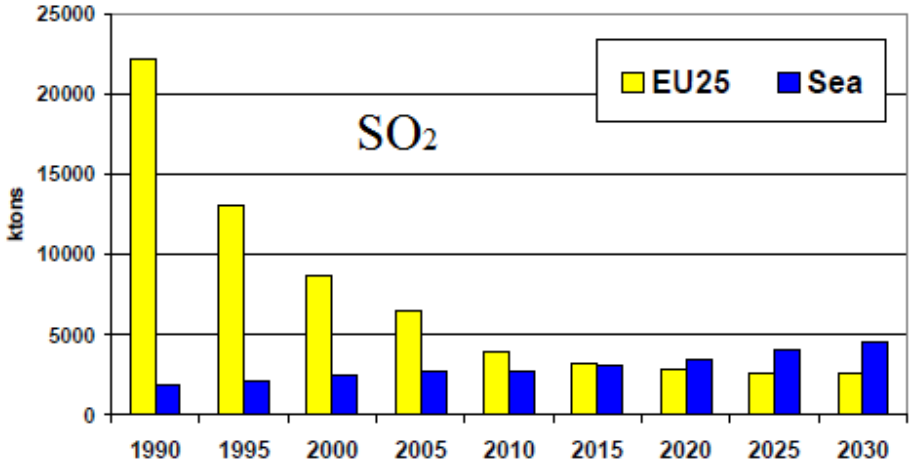
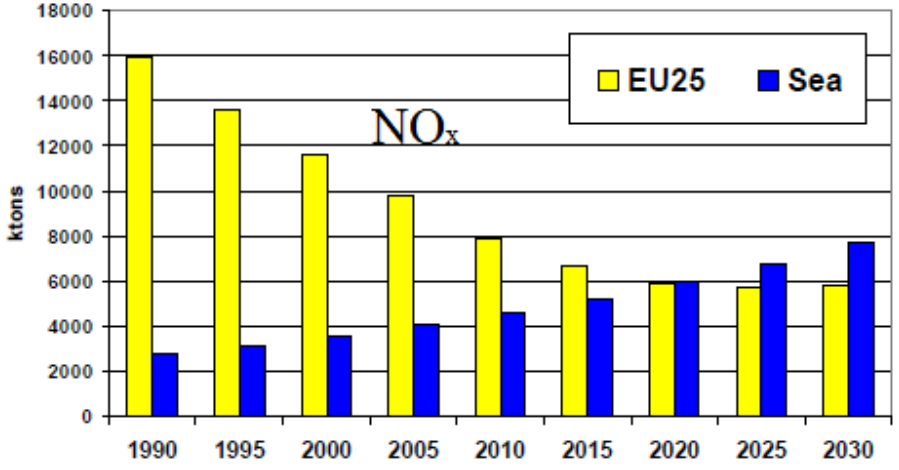
NOx and SOx Production







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Emission Control Areas

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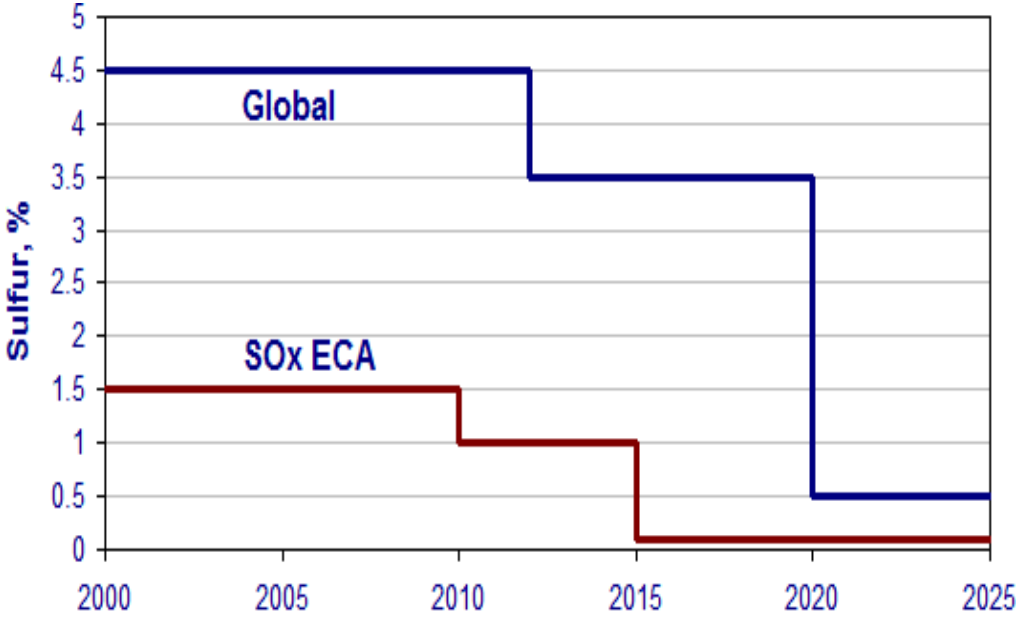
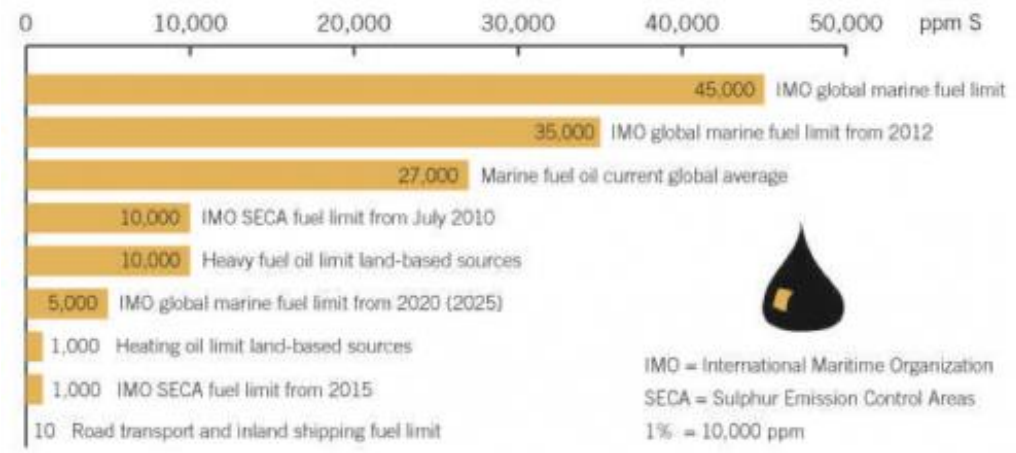
MARPOL Limits





1.5% = 6g SO_2/kWh

Limit is only on SO_2, but it is well-known that NO_x and VOC limits are coming

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NA Fines

	Table 3	
Actual Fuel Sulfur Content, % m/m[14]	Penalty over duration of violation, first offense – Table 3 ($)	
	Violation of 1.00% sulfur limit (**U** = MT of fuel burned while in the U.S. ECAs)	Violation of 0.10% sulfur limit (**U** = MT of fuel burned while in the U.S. ECAs)
3.5 or higher	$400*U	$750*U
3.0	$350*U	$700*U
2.5	$300*U	$650*U
2.0	$250*U	$600*U
1.5	$200*U	$550*U
1.25	$150*U	$500*U
1.10	$100*U	$450*U
1.00	N/A	$400*U
0.80		$350*U
0.60		$300*U
0.40		$250*U
0.20		$200*U
0.15		$150*U
0.10		N/A

U ~ 50 tons/day

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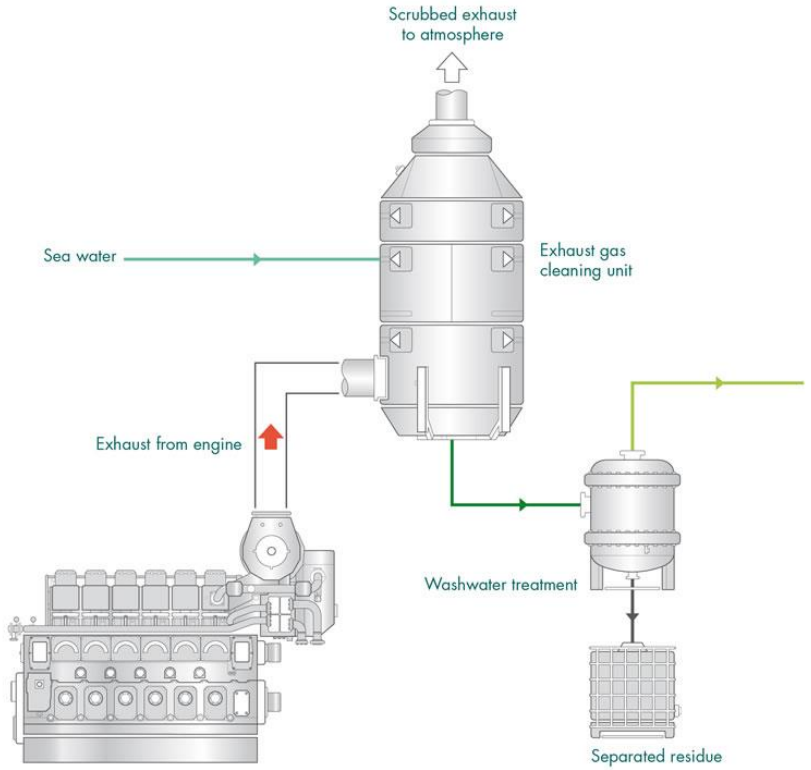
Main Solutions

1) Low sulphur fuel:
   - works
   - but only for SO_2
   - costs >2 x current fuel

2) SO_2 scrubbing:



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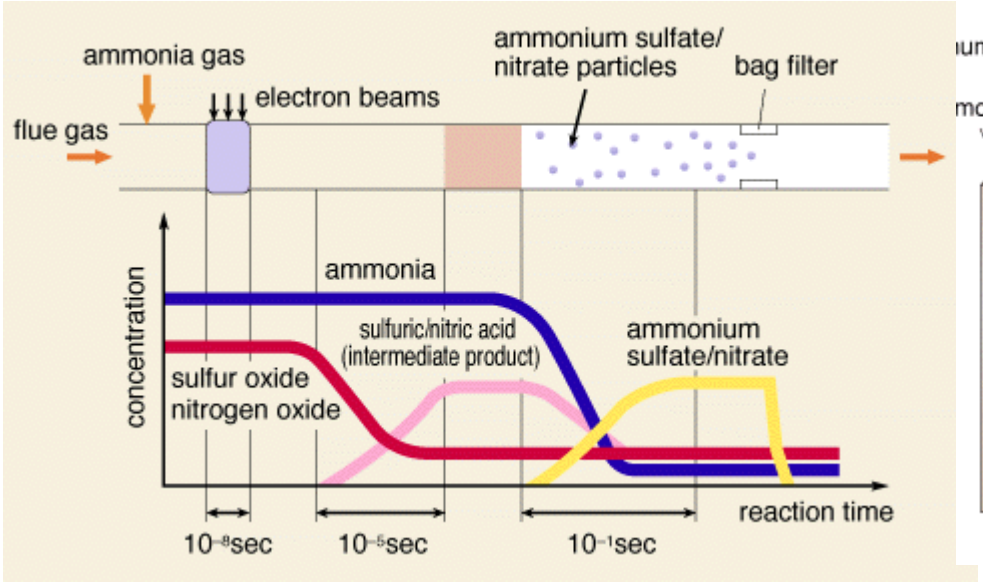
Main Solutions

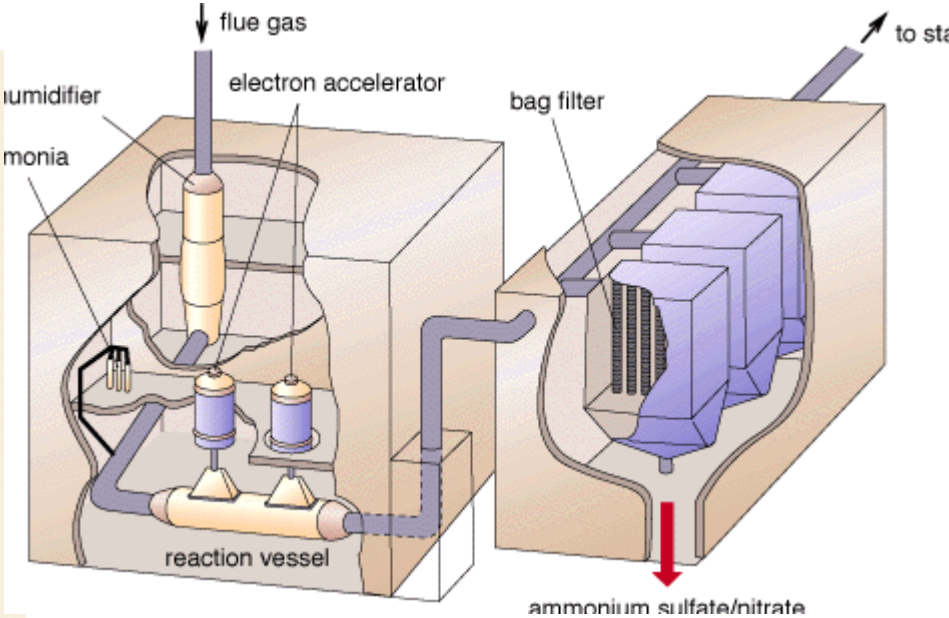
1) Low sulphur fuel:
   - works
   - but only for SO_2
   - costs >2 x current fuel

2) SO_2 scrubbing:
   - works
   - costs about 1 MEUR to install
   - requires about 1 month in dry dock
   - >50% bigger than standard exhaust systems
   - does not work for NO_x or VOC
   - separate NO_x system would be required and is incompatible

Electron Beams

- Have been used for removal of NOx, SOx and VOC from power stations
- 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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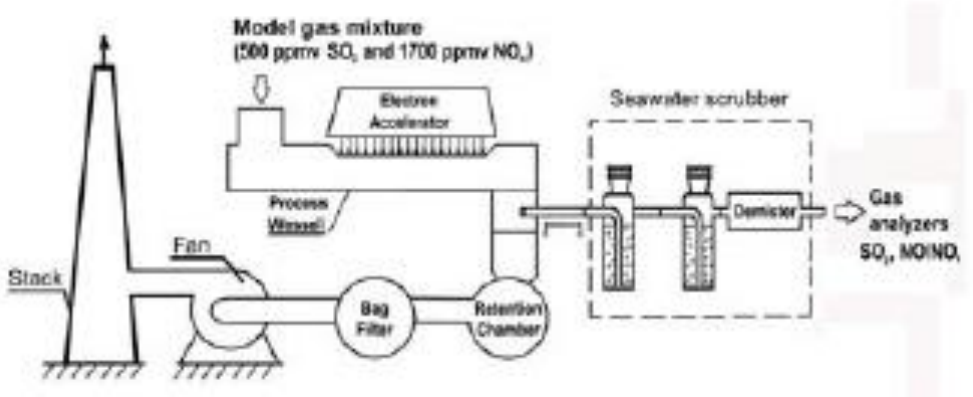
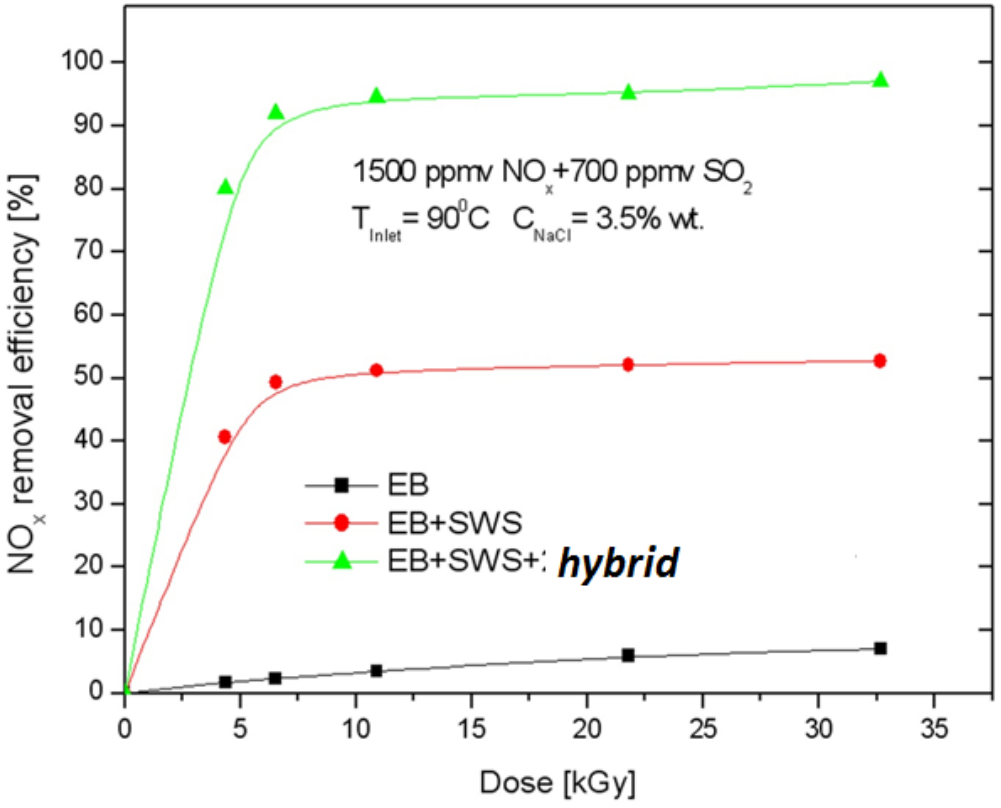
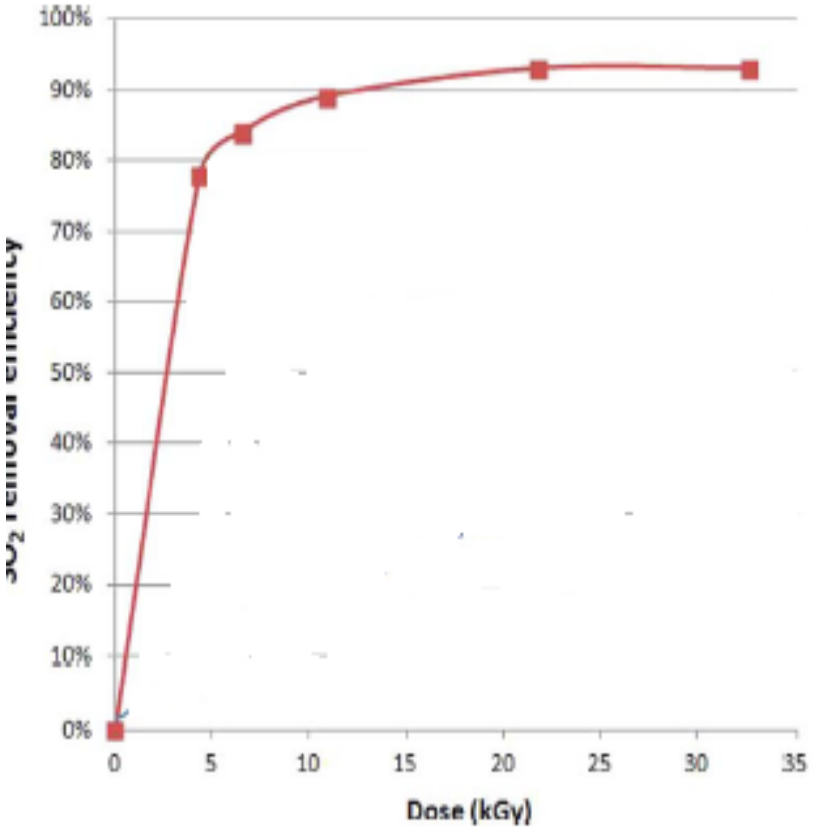
Marine Exhaust

- Tested in the lab by adding correct concentrations of gases



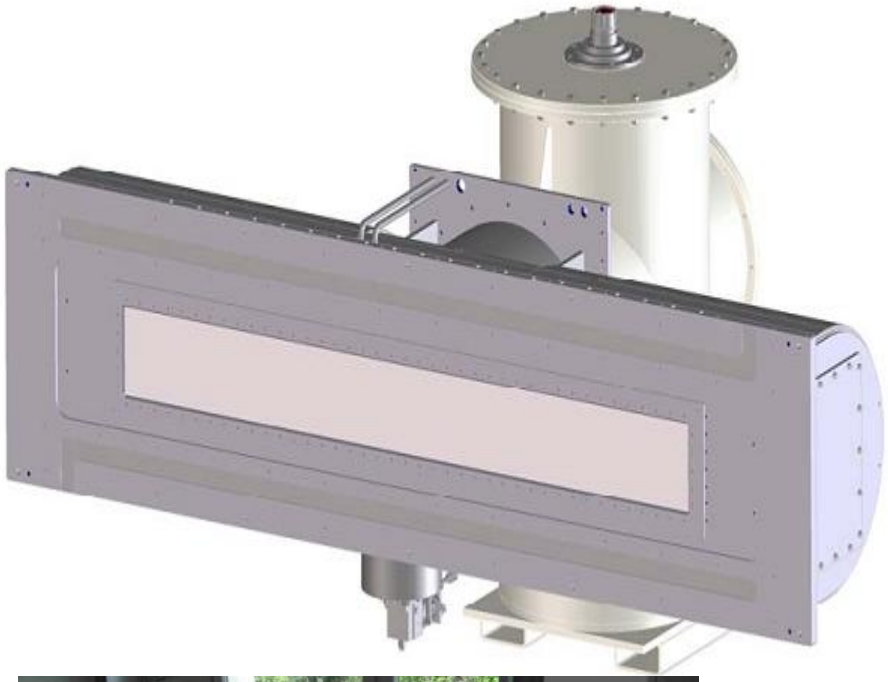
Marine Exhaust

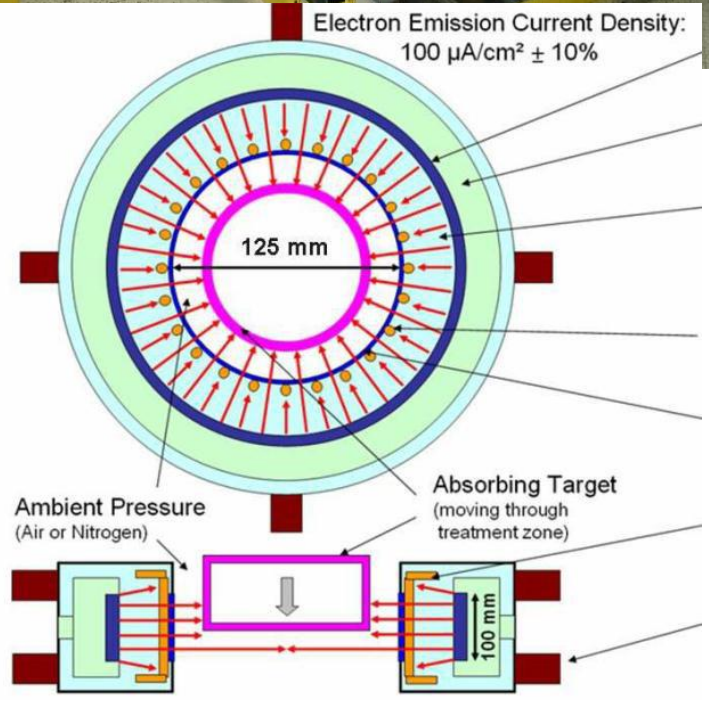


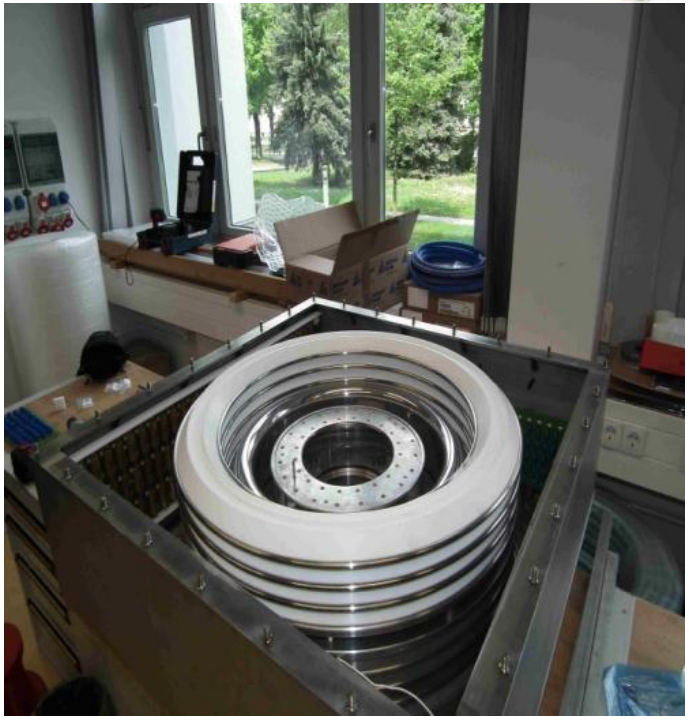


- Next step: test with marine diesel engine on land


ESI
EZCure




Electron Emission Current Density:
100 µA/cm² ± 10%
125 mm
Ambient Pressure
(Air or Nitrogen)
Absorbing Target
(moving through
treatment zone)
100 mm



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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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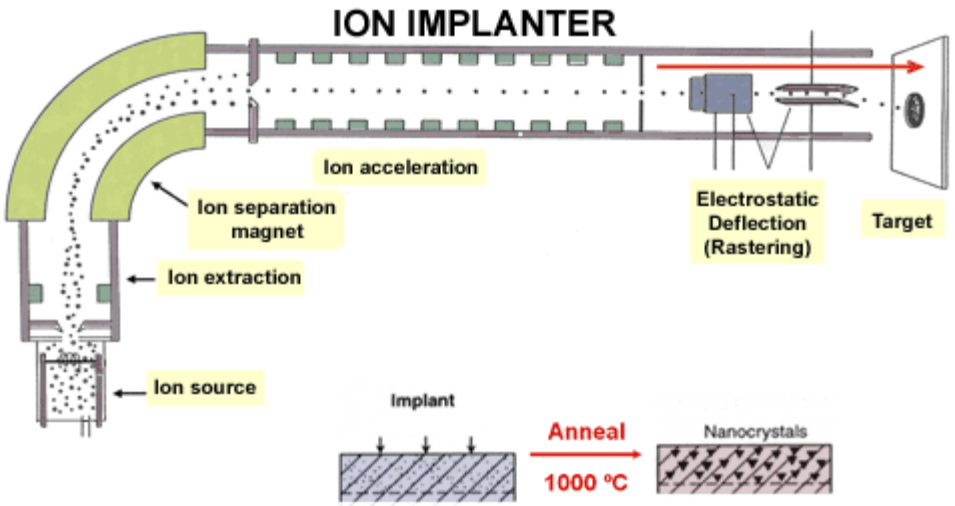
Ion Implantation



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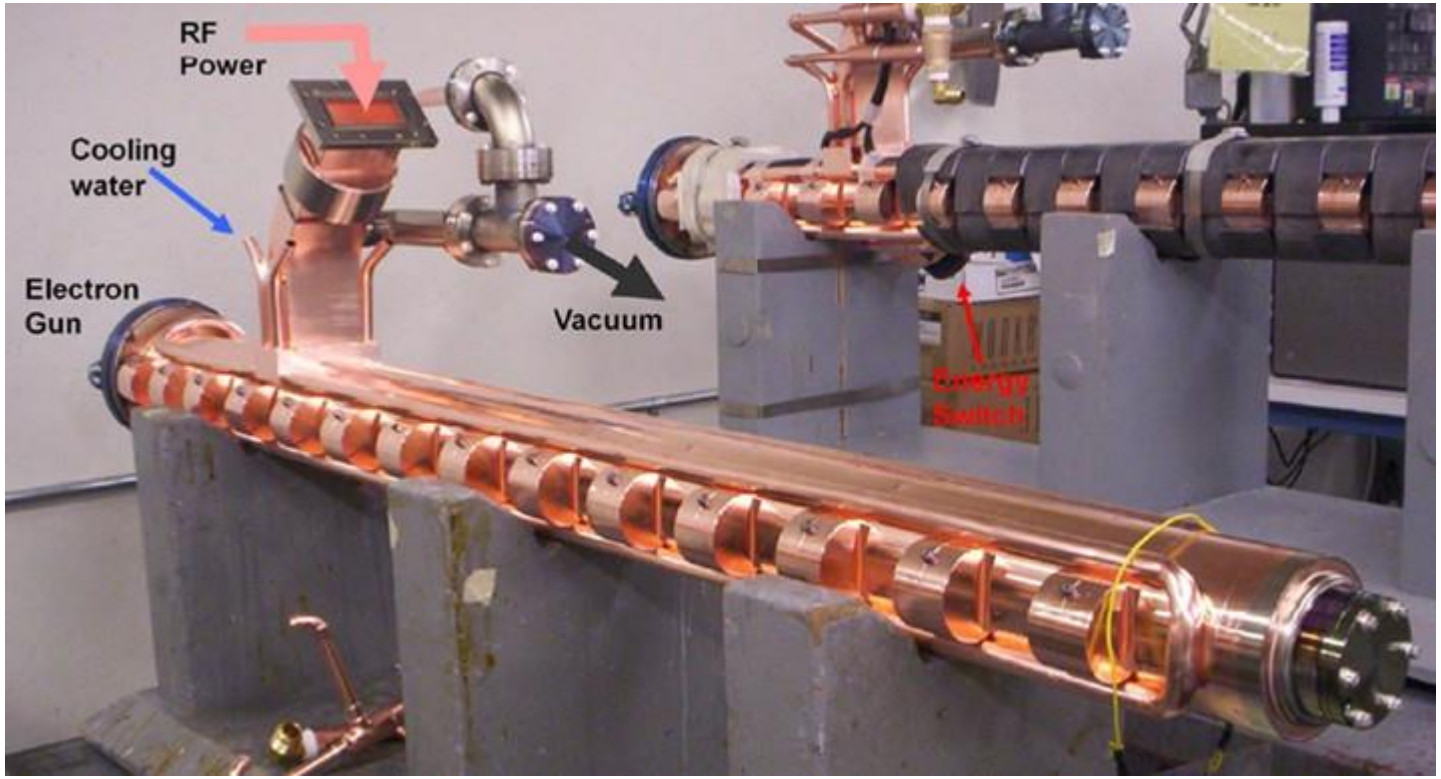
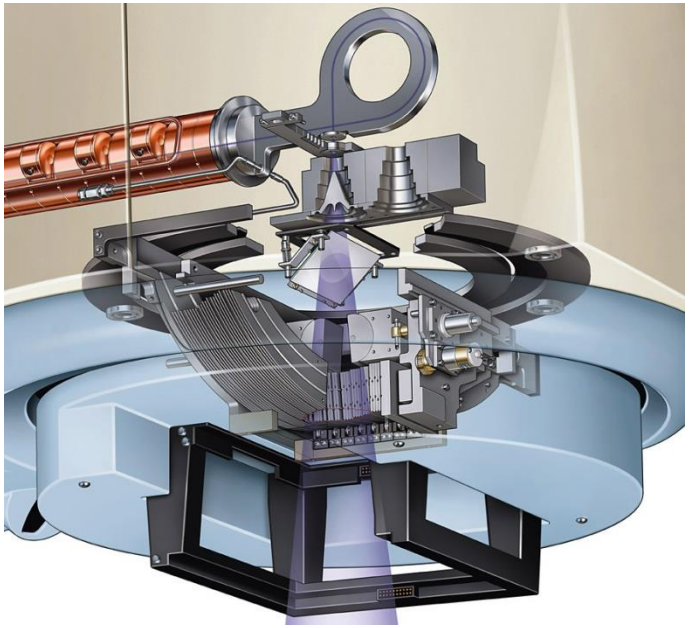
Medical: Cancer Therapy

- Radiotherapy uses ionising radiation
- X-rays, e, p, C, α, β, n, etc
- Predominantly, x-rays created using electron linac



Health: Radiotherapy

- Most radiotherapy uses X-rays for cancer treatment
- Created using electron linear accelerator
- Commercially manufactured
- Energy ~4-20 MeV
- >13000 systems in the World



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Beam Delivery

CyberKnife

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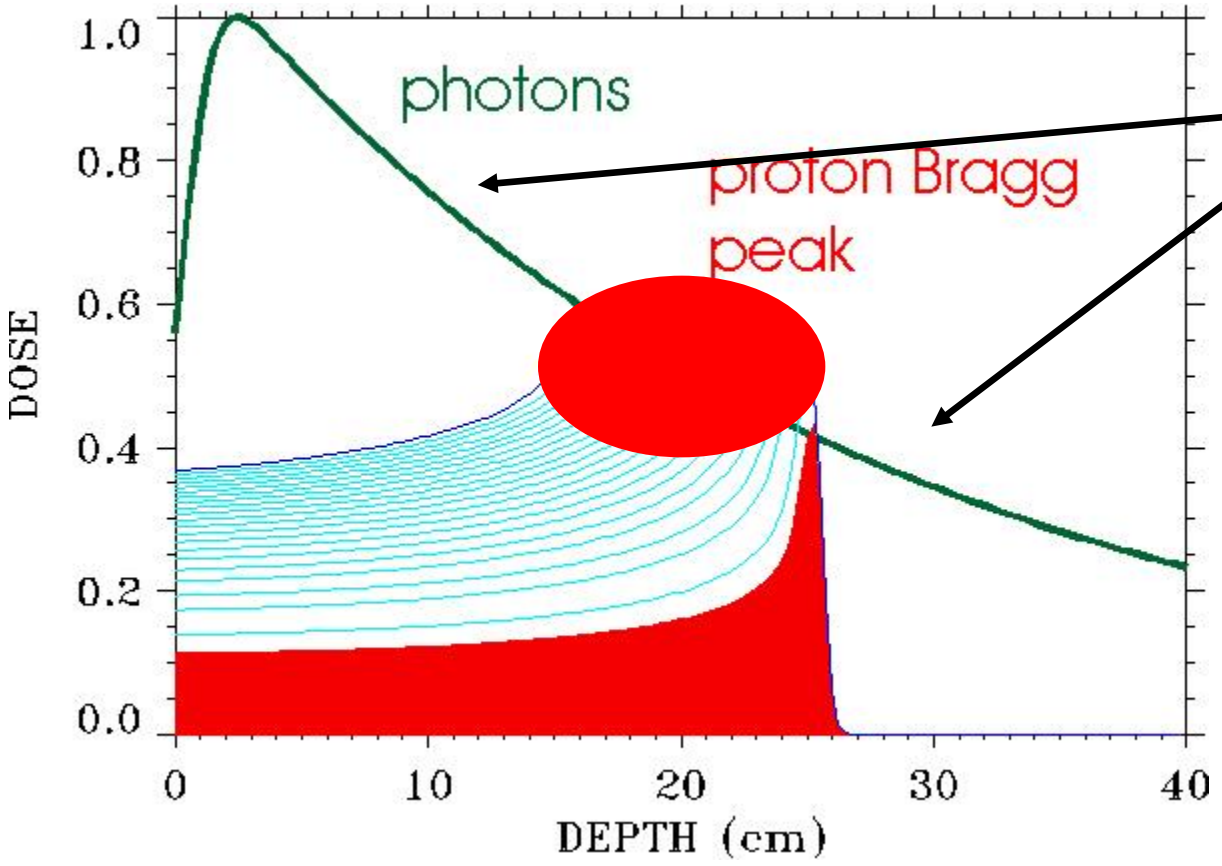
Dose Localisation



Damage to healthy tissue: side-effects!

But…. healthy cells have more repair mechanisms…

Very sophisticated techniques used to deliver therapy:

Fractions, IMRT, IGRT, etc

It's possible to do better!

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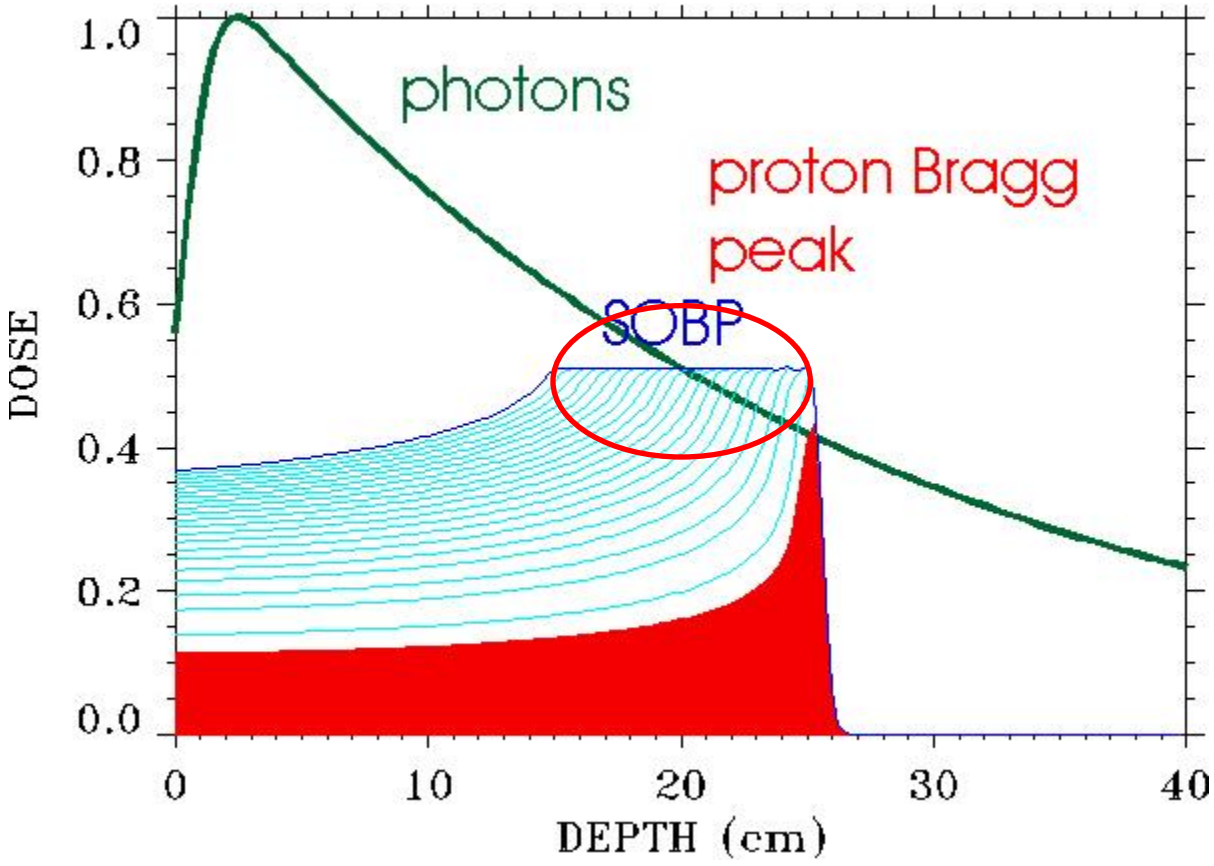
Dose Localisation



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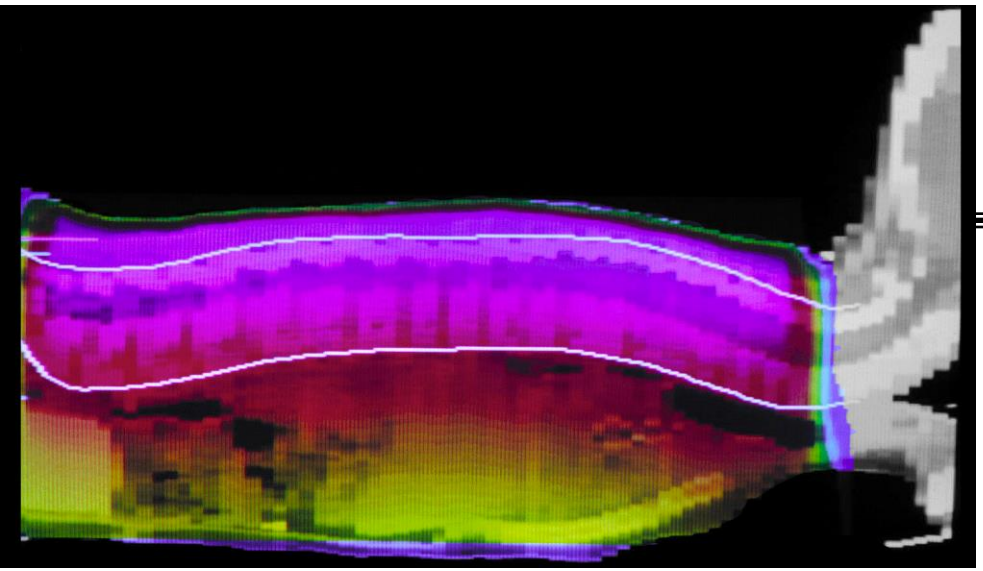
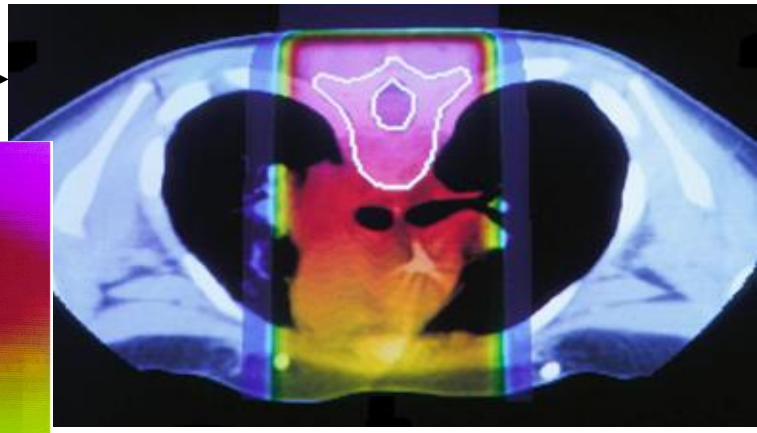
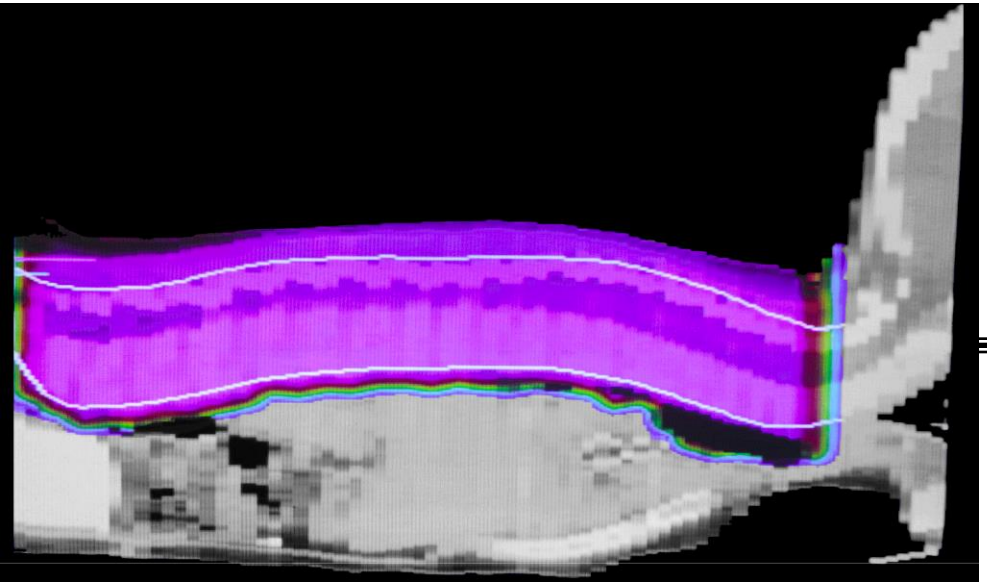
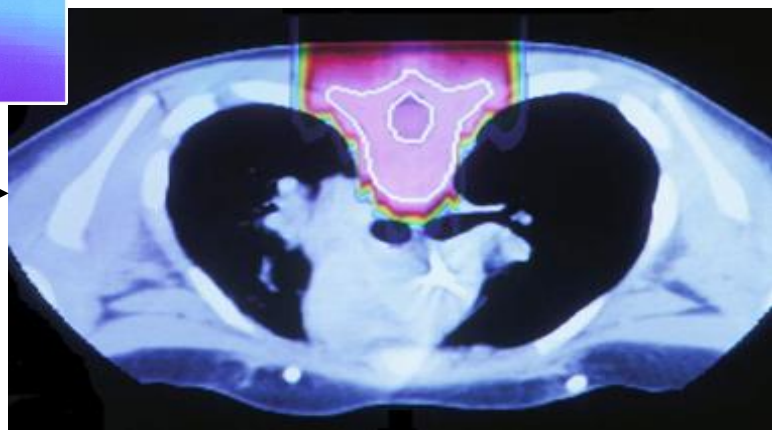
Dose Localisation

Medulloblastoma in a child (MD Anderson)









100%

60%

10%

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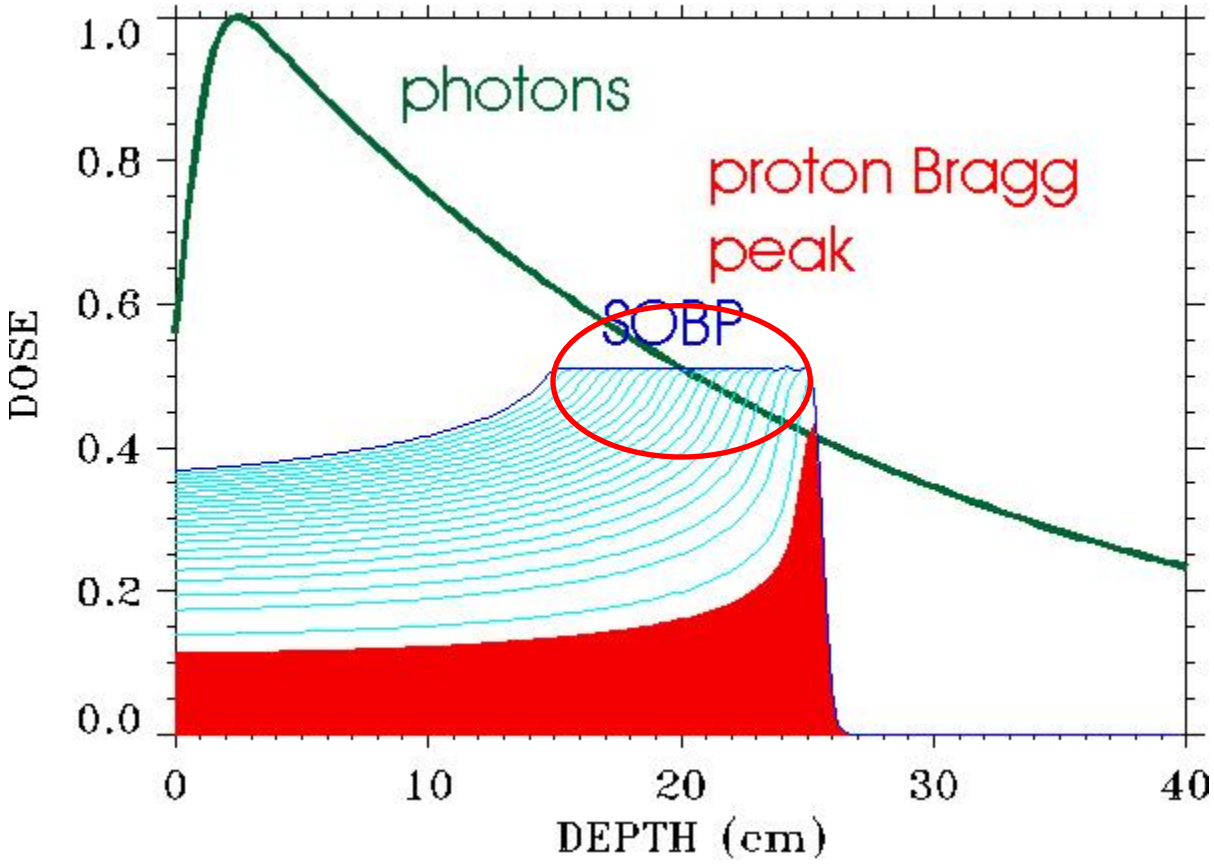
Dose Localisation



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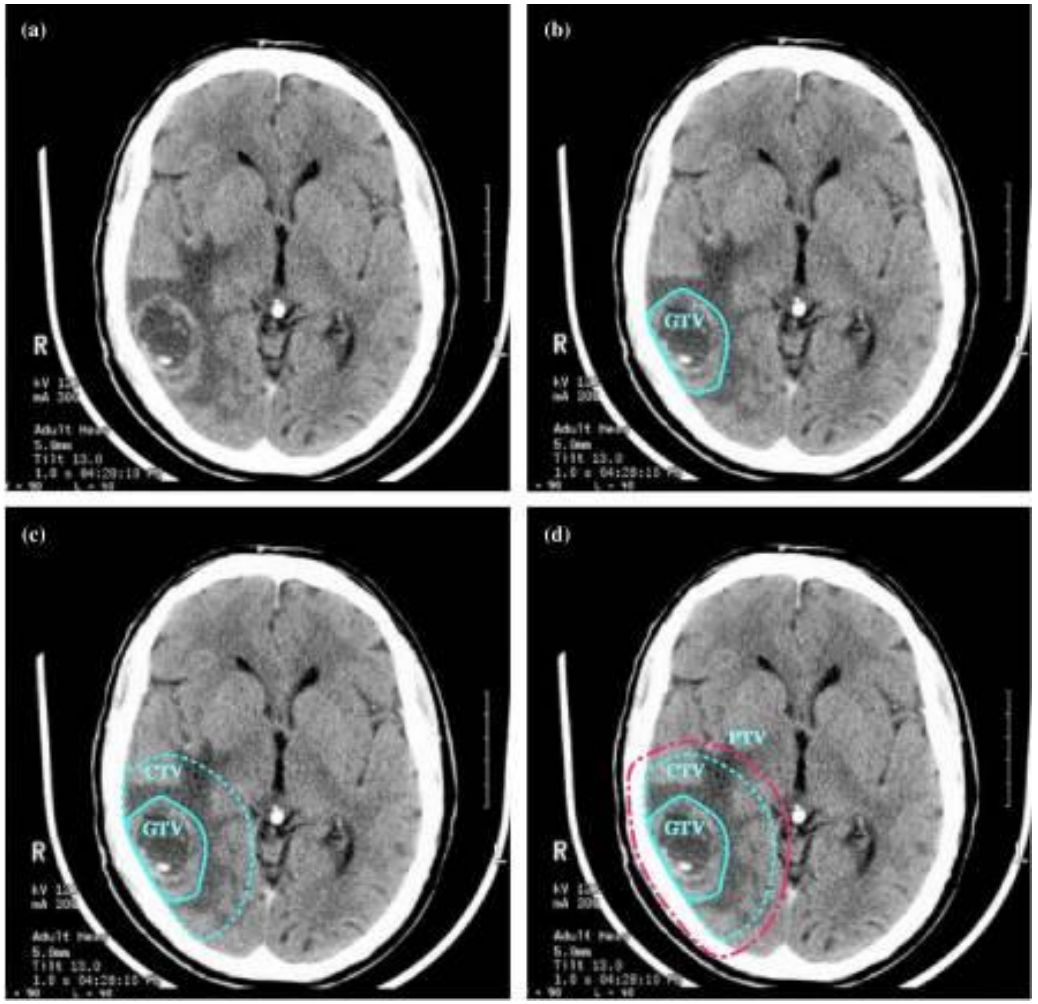
Proton Therapy

Other problems:
- RBE
- imaging

Gross tumour volume:
- what you can see

Clinical target volume:
- unseen spread

Planning target volume:
- allows for errors



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Proton Therapy

Mitsubishi synchrotron

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Proton Therapy

IBA gantry

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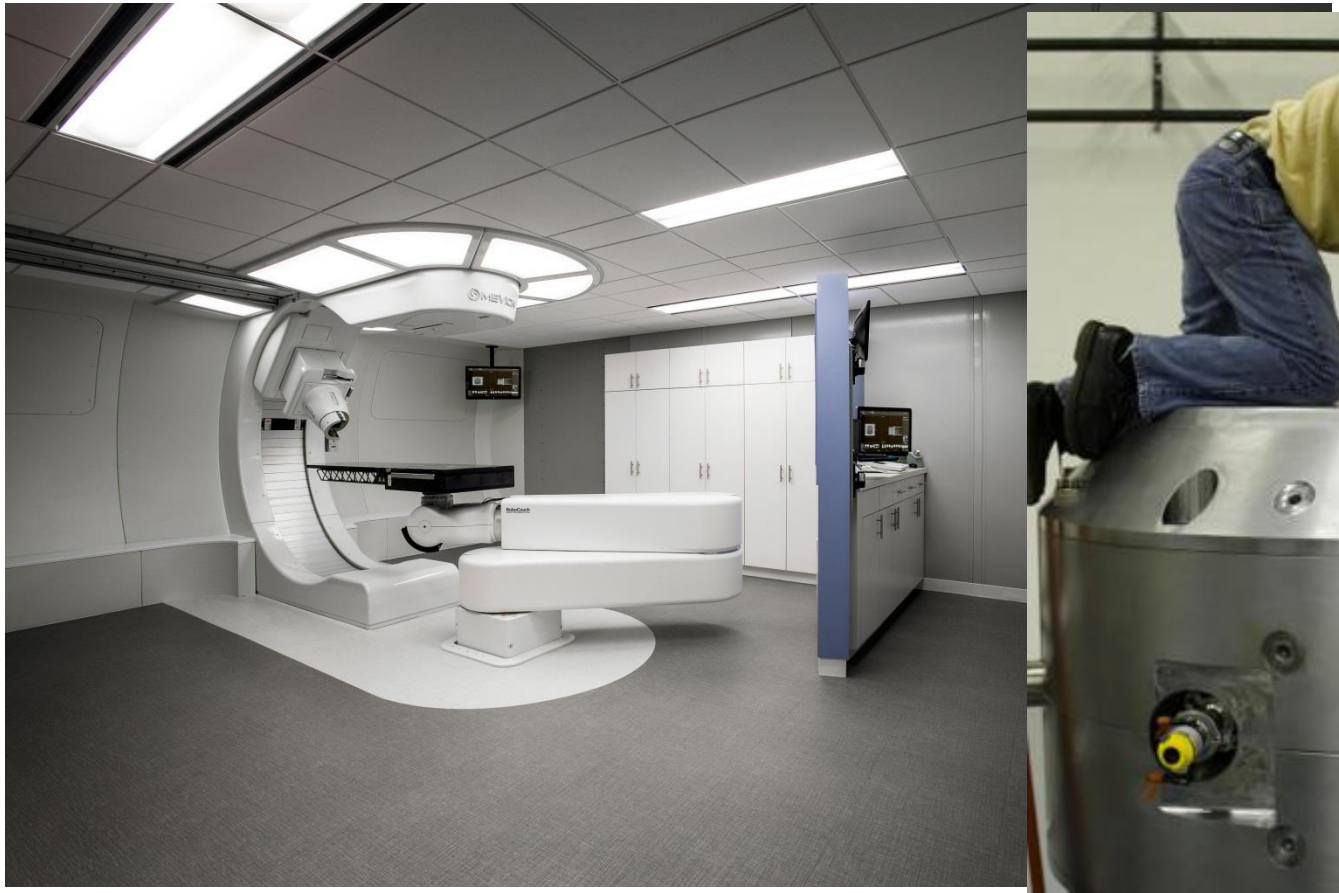
Proton Therapy



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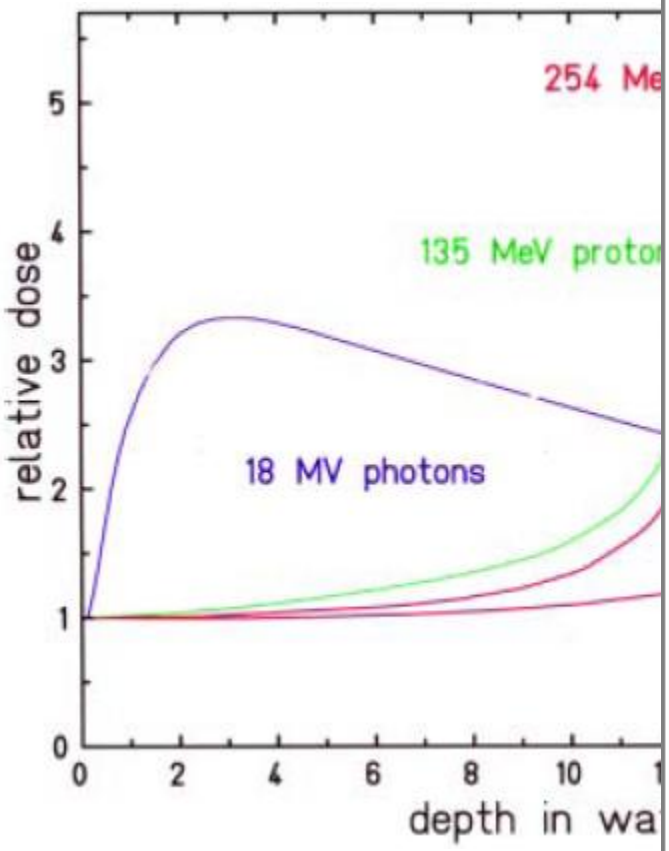
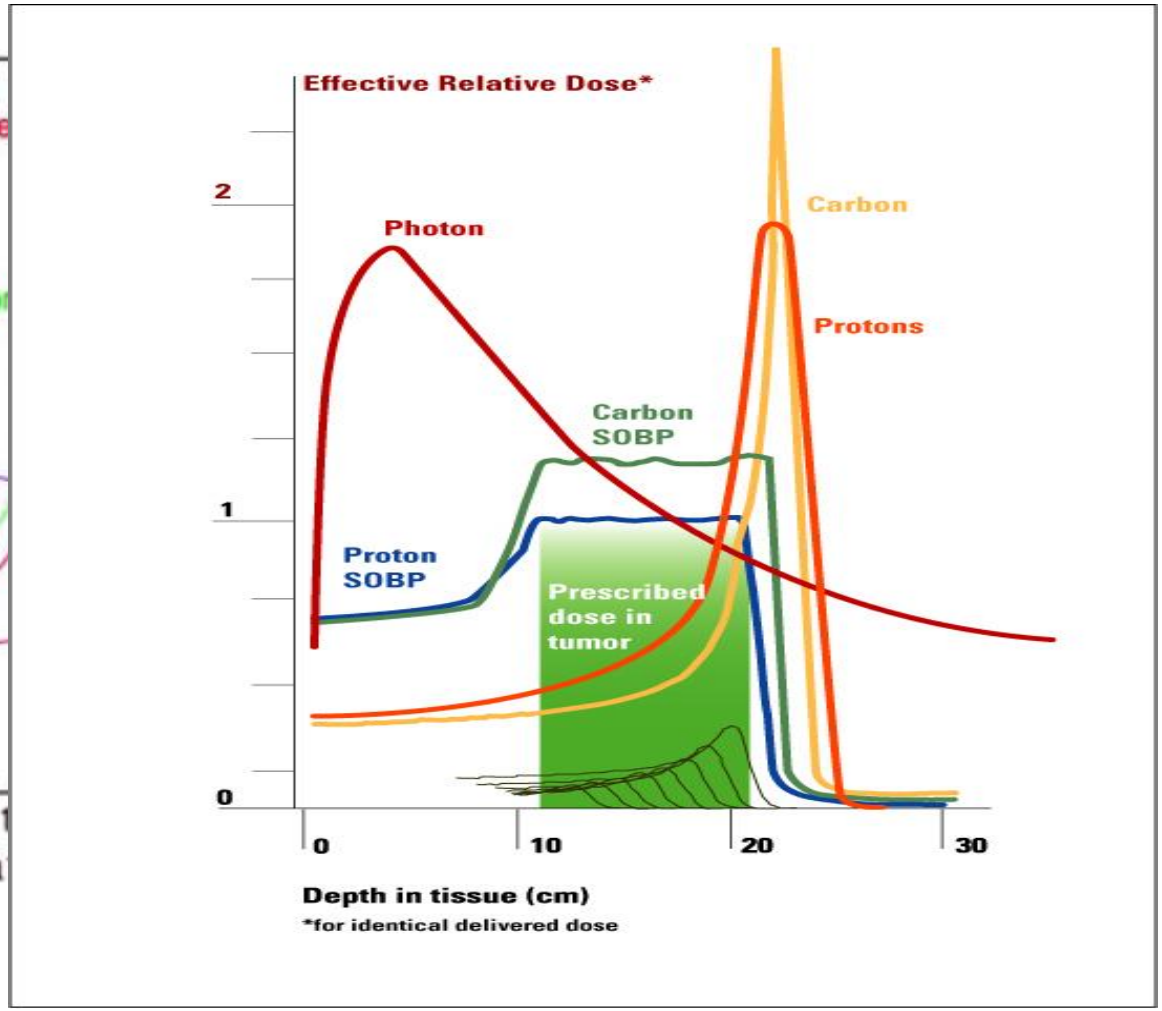
Dose Localisation





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Dose Localisation

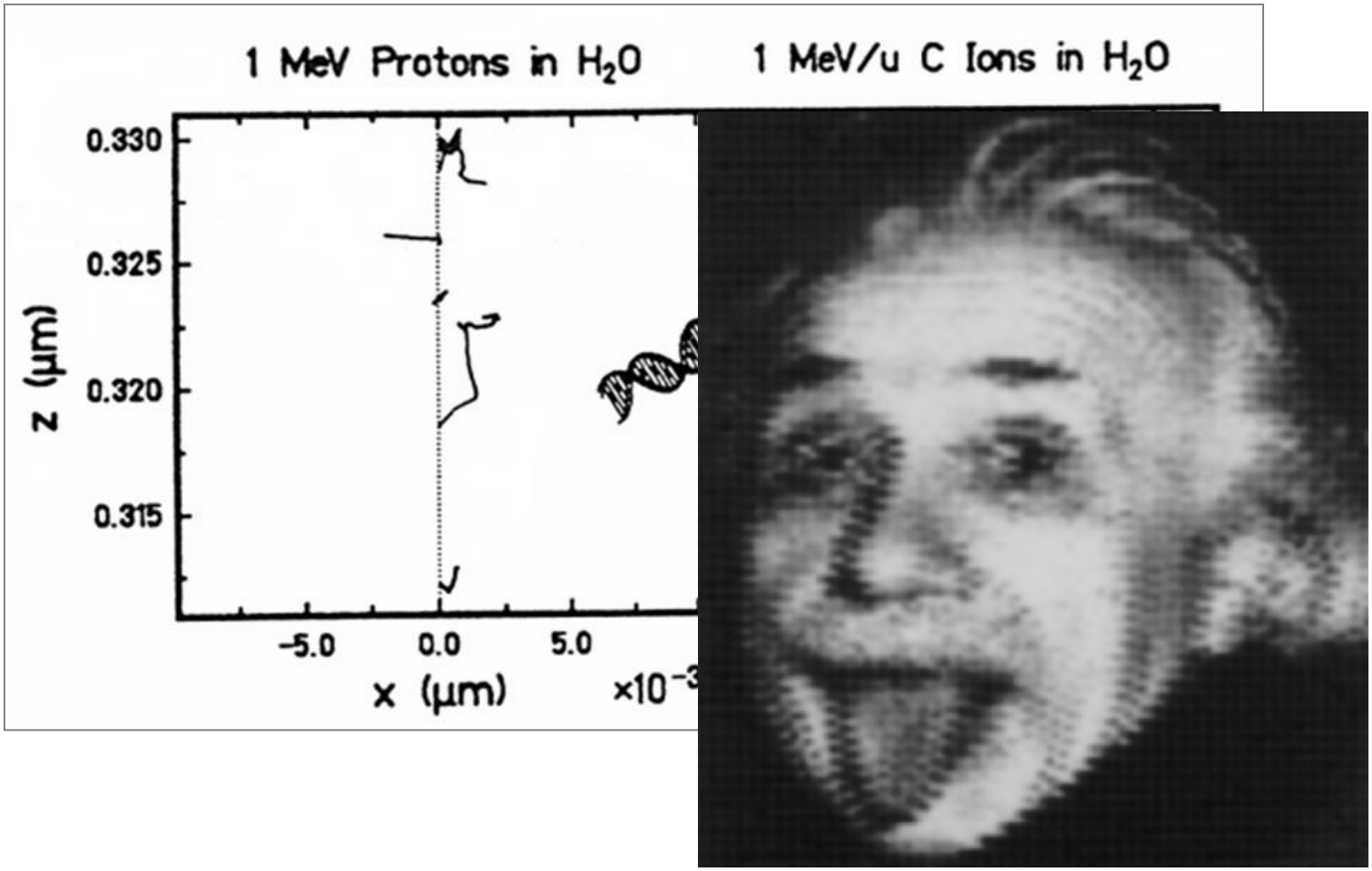

Image using 430 MeV/u carbon beam at GSI

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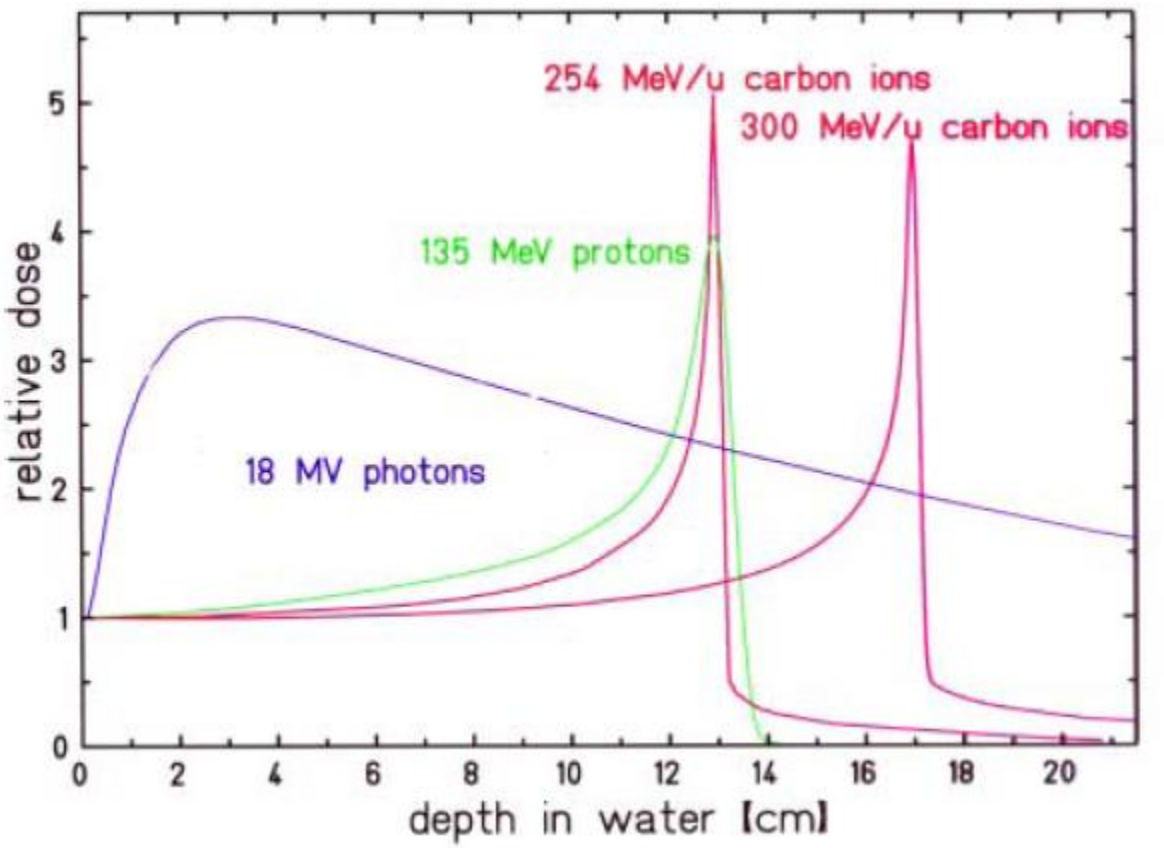
Dose Localisation



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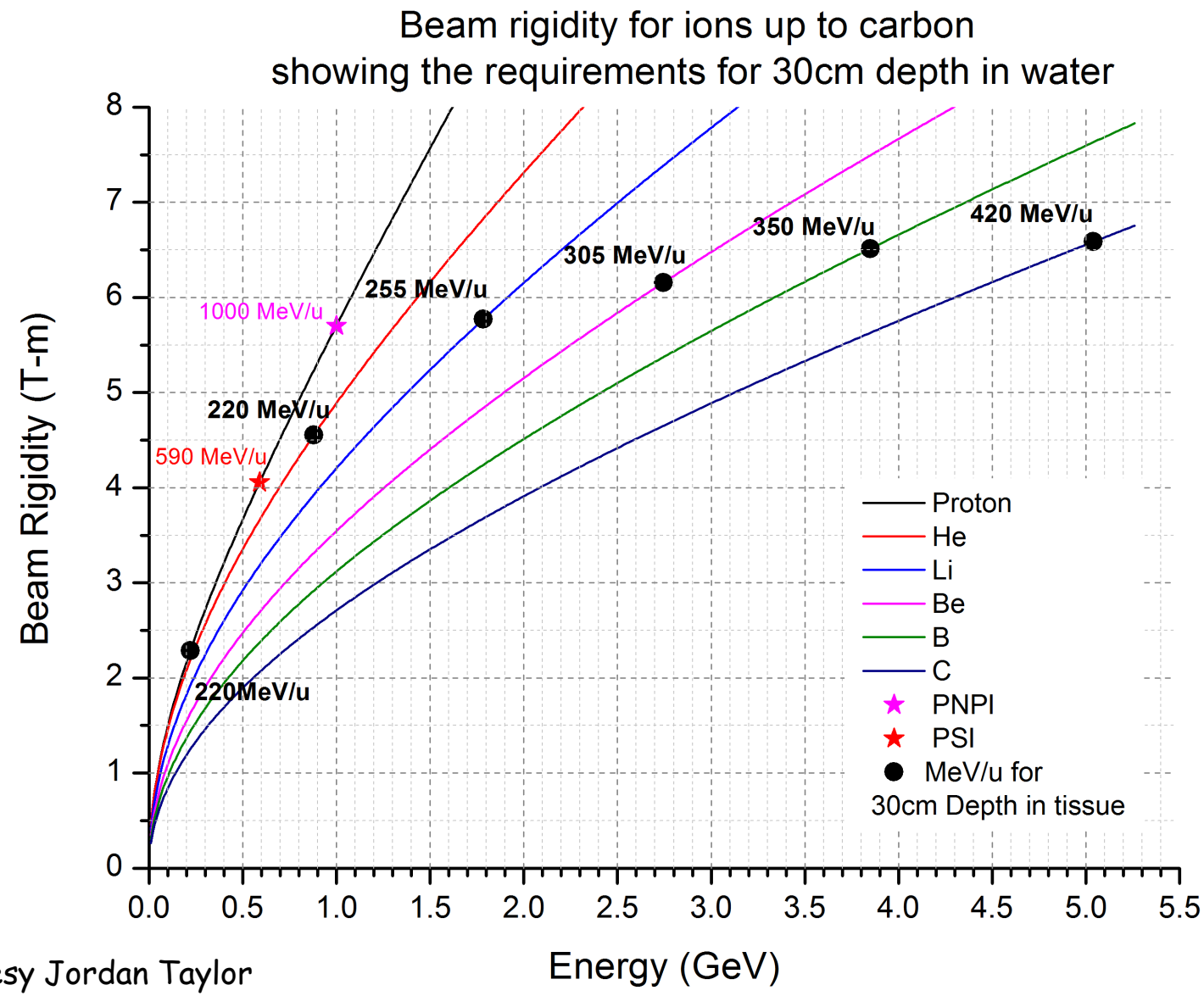
Ion Therapy Energies



Courtesy Jordan Taylor

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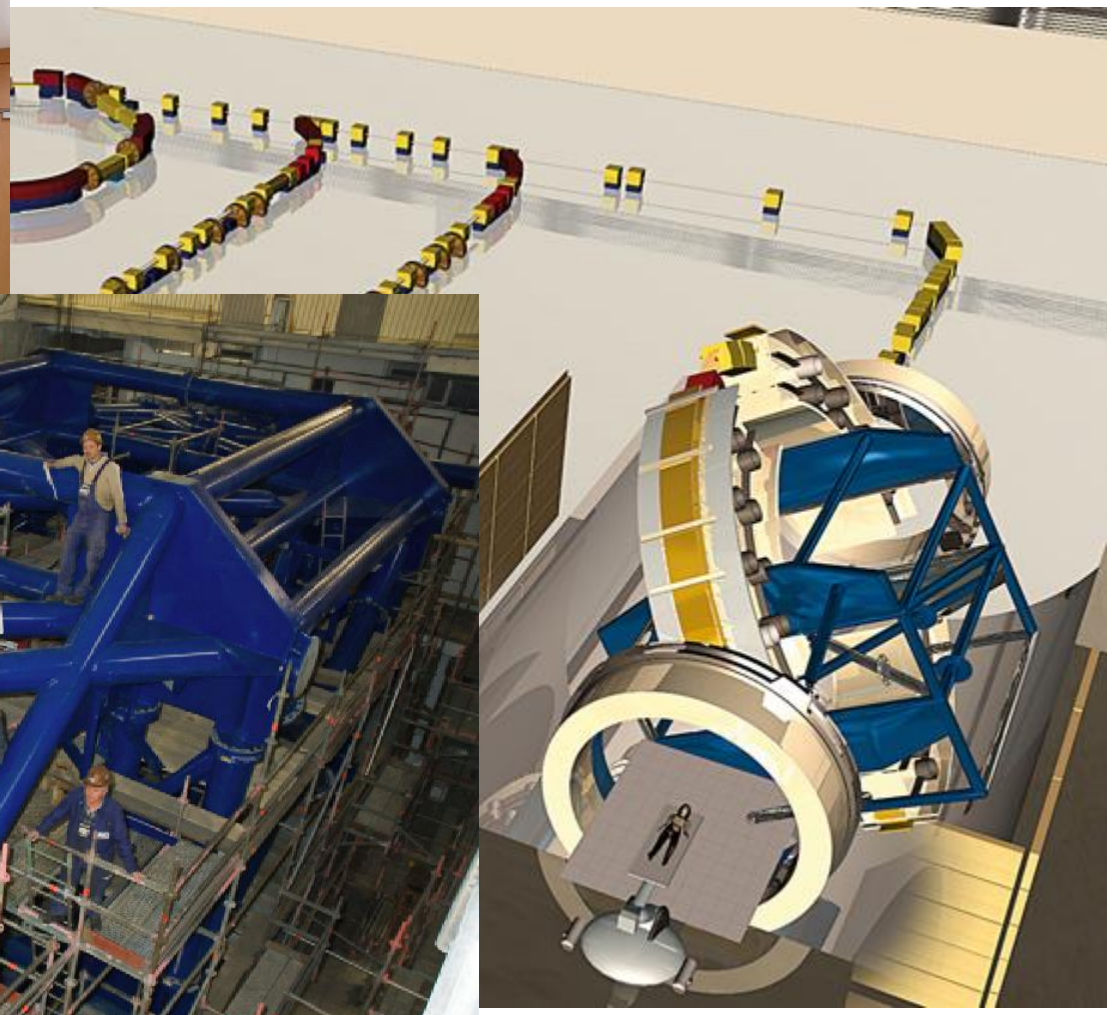
Carbon Therapy



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Carbon Therapy

- In operation:
  - Europe: 4
  - China: 2
  - Japan: 5
- Construction:
  - Europe: 0
  - China: 2
  - Japan: 1
  - South Korea: 1
- Significant PP input to those in Europe
- Two based on CERN design
- Main problem: size!
- Interest in helium
- New types of accelerator

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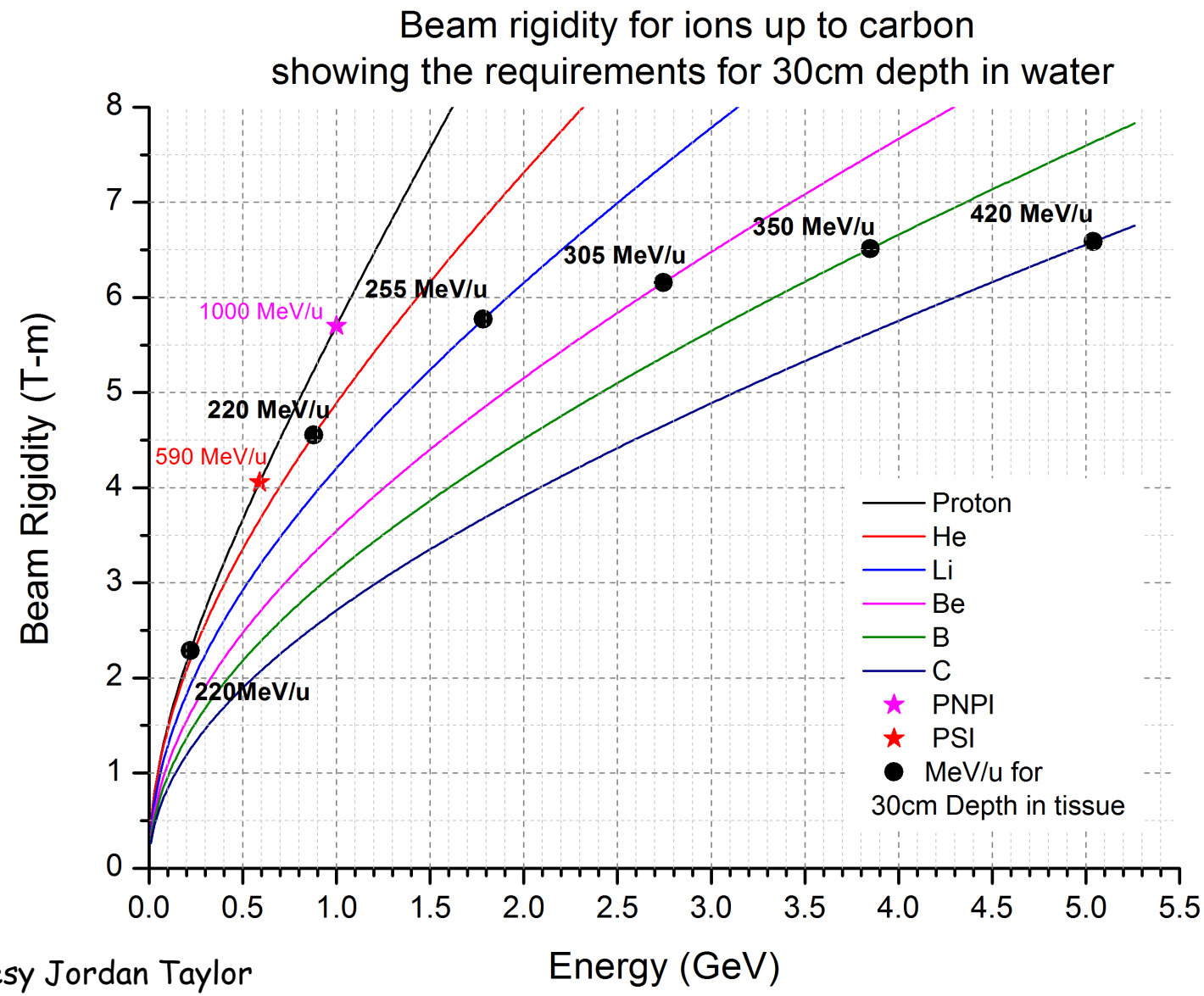
Ion Therapy Energies



Courtesy Jordan Taylor

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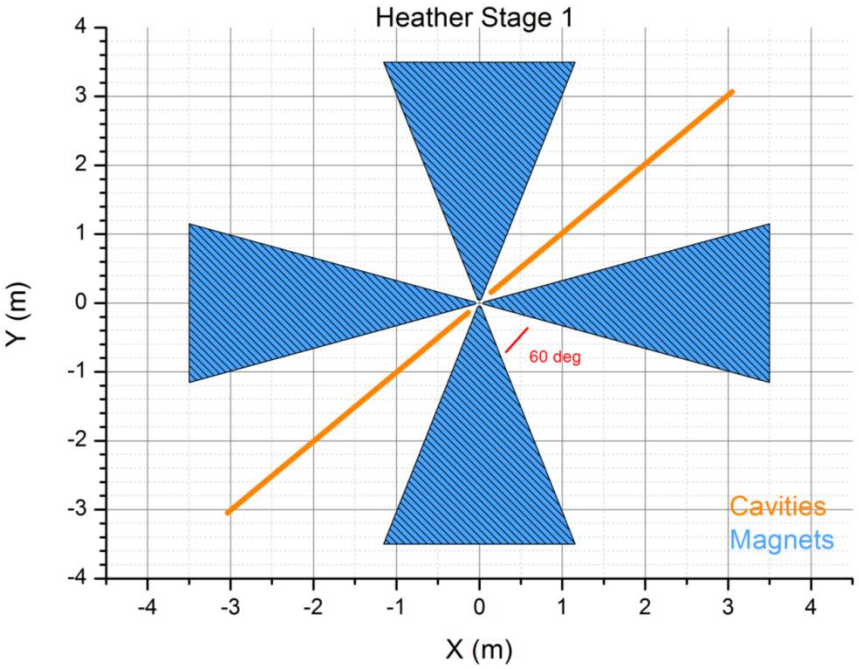
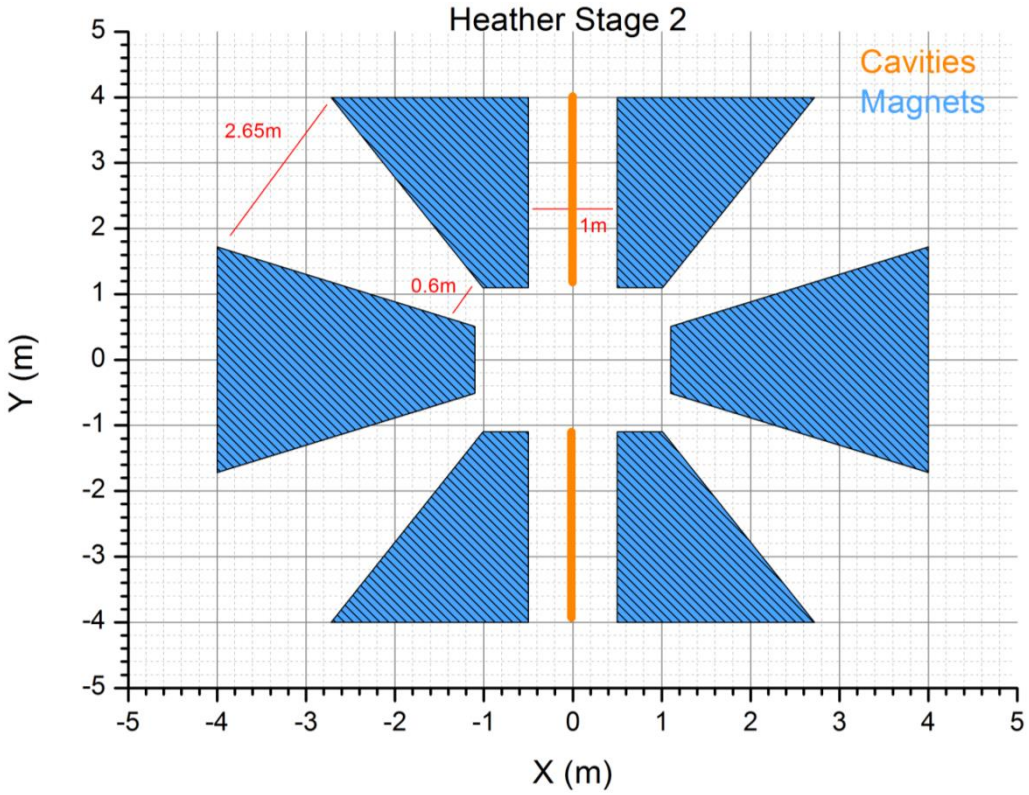
Helium Ion Therapy





Courtesy Jordan Taylor

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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
- Getting funding is not easy!
- For more information see:
  - Applications of Particle Accelerators in Europe:
    http://apae.ific.uv.es/apae/
  - Accelerators for Society:
    http://www.accelerators-for-society.org/
  - Accelerators for America's Future:
    http://www.acceleratorsamerica.org/

Conclusions (part 1)

- Particle accelerators are not just the LHC
- Extensively used in industry
- Mainly industrially manufactured
- Reliable
- Relatively easy to use