Applications of FFAs

FFA School
Coseners House, Abingdon, UK
September 2022

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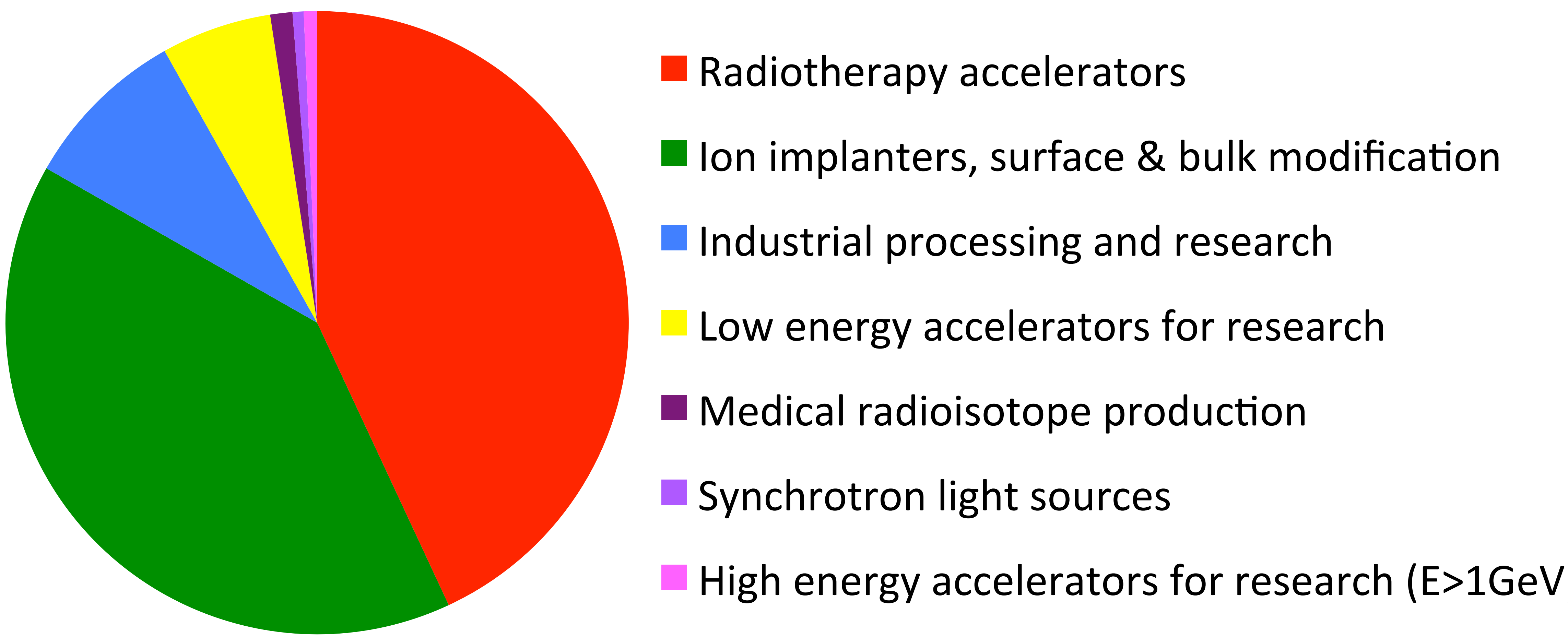
University of Melbourne
University of Oxford

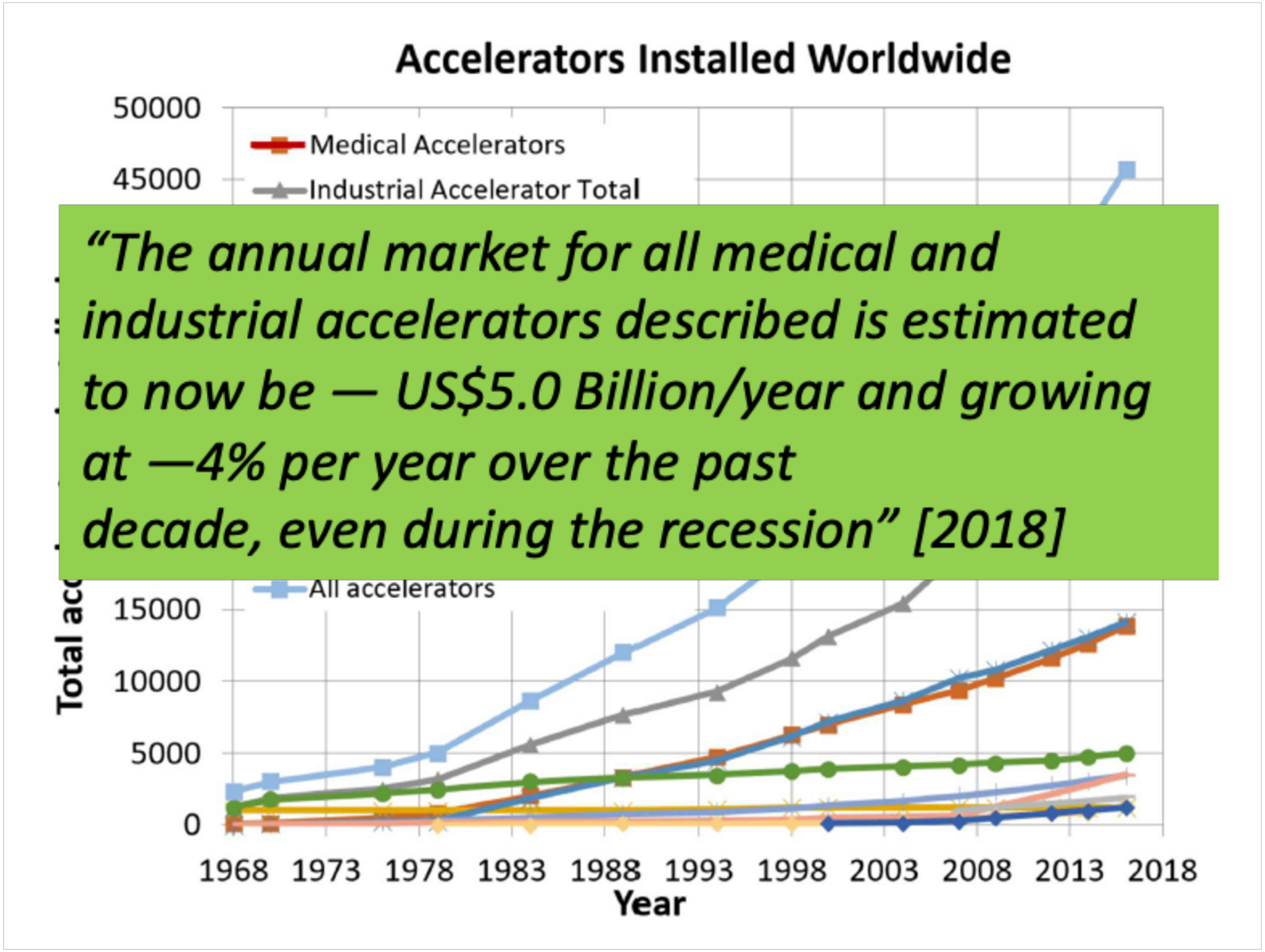
"A beam of particles is a very useful tool..."

-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011



~30,000 accelerators in the world
(not including CRT televisions…)

Science & Technology Facilities Council



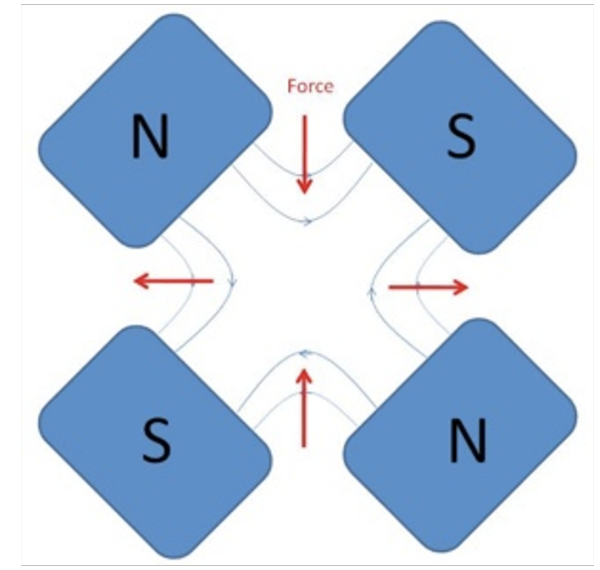
"The annual market for all medical and industrial accelerators described is estimated to now be — US$5.0 Billion/year and growing at —4% per year over the past decade, even during the recession" [2018]

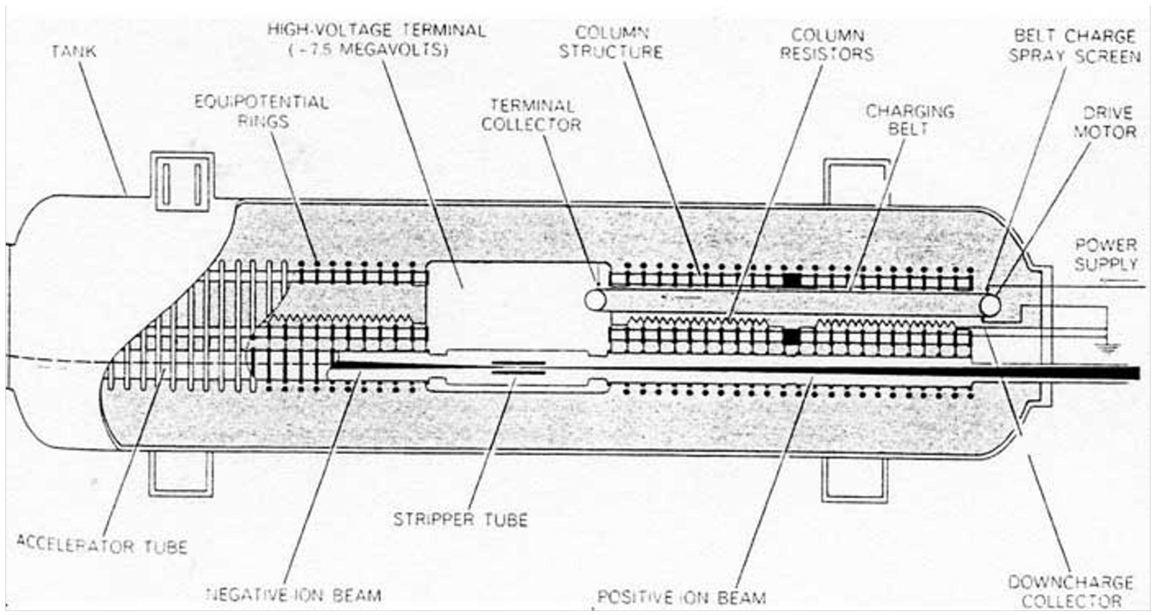
Doyle, McDaniel, Hamm, *The Future of Industrial Accelerators and Applications, SAND2018-5903B*

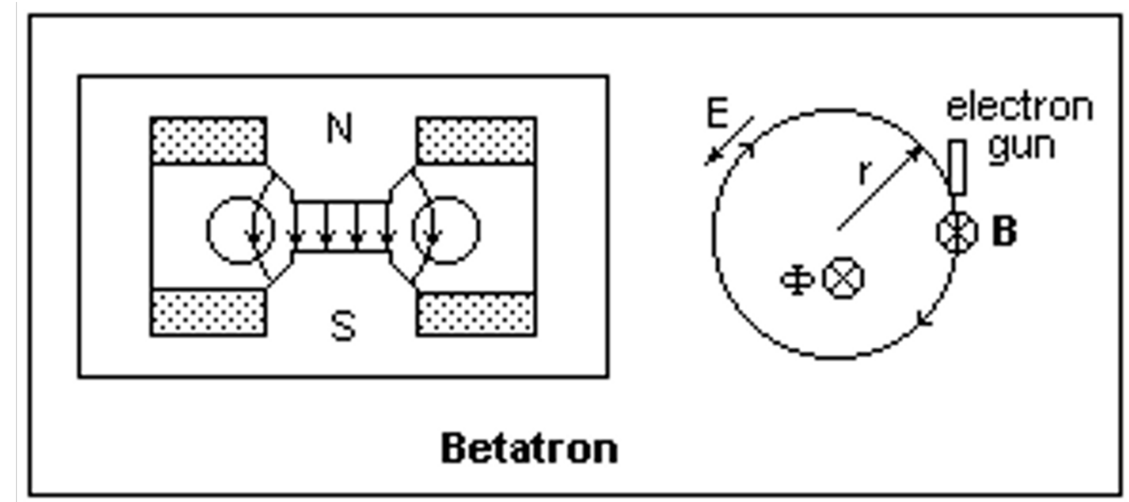
Outline

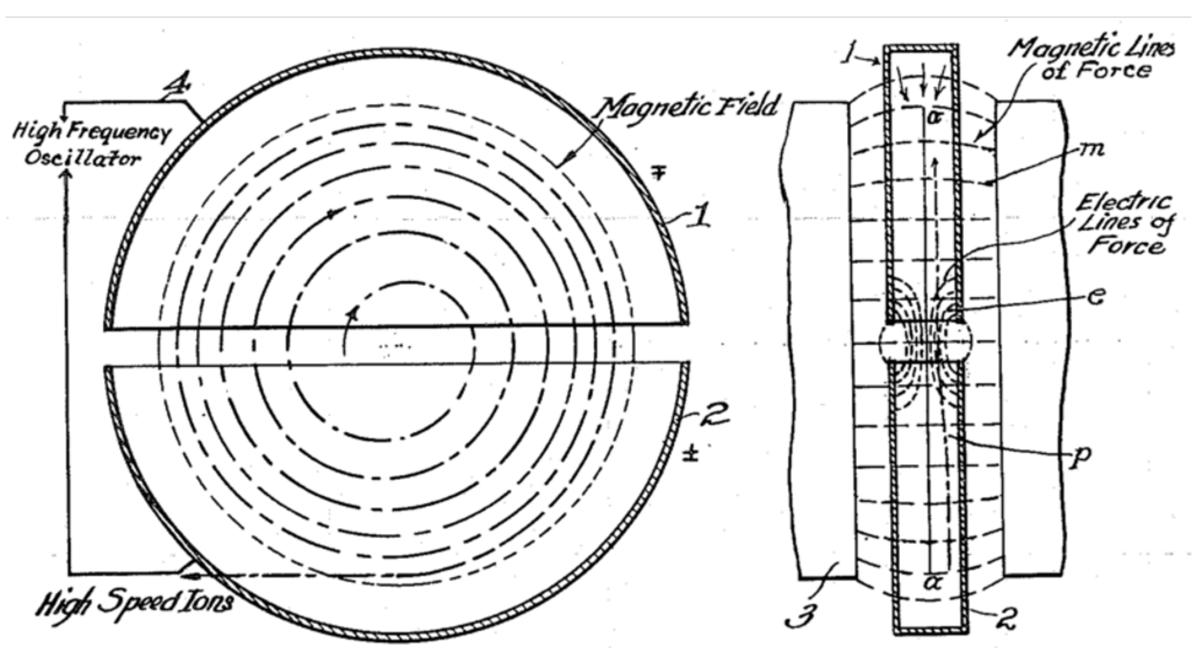
1. Particle physics: colliders?
2. Medical applications & requirements
3. High power proton drivers
4. Cost-effective accelerators

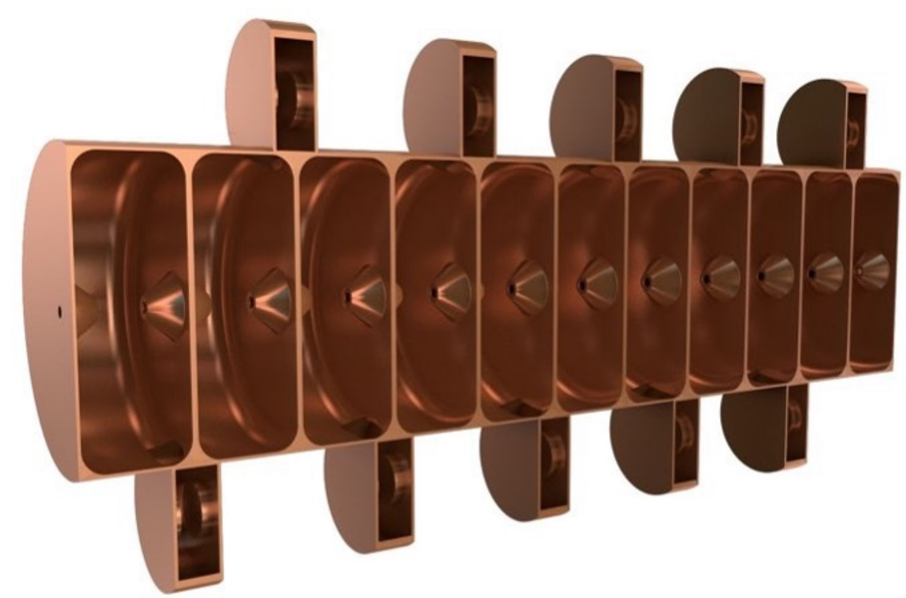
There are many types of accelerators. Why choose an FFA?











Well, we already saw advantages:

Advantages of FFAs

- Interesting for
  - high repetition rate (source of secondary particles, medical accelerators).
  - rapid acceleration (short-lived particles),
  - very high power machines (proton drivers, ADSR),
  - handling of big beams (muon machines, internal target),
  - reliable machines (ADSR, medical accelerators),
  - energy-efficient machines (ADSR).

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Some challenges for future accelerators

High power

Neutrons, muons, ADS

Reliable

Medical, ADS

Flexible

Is industry limited by existing technology?

Rapid acceleration

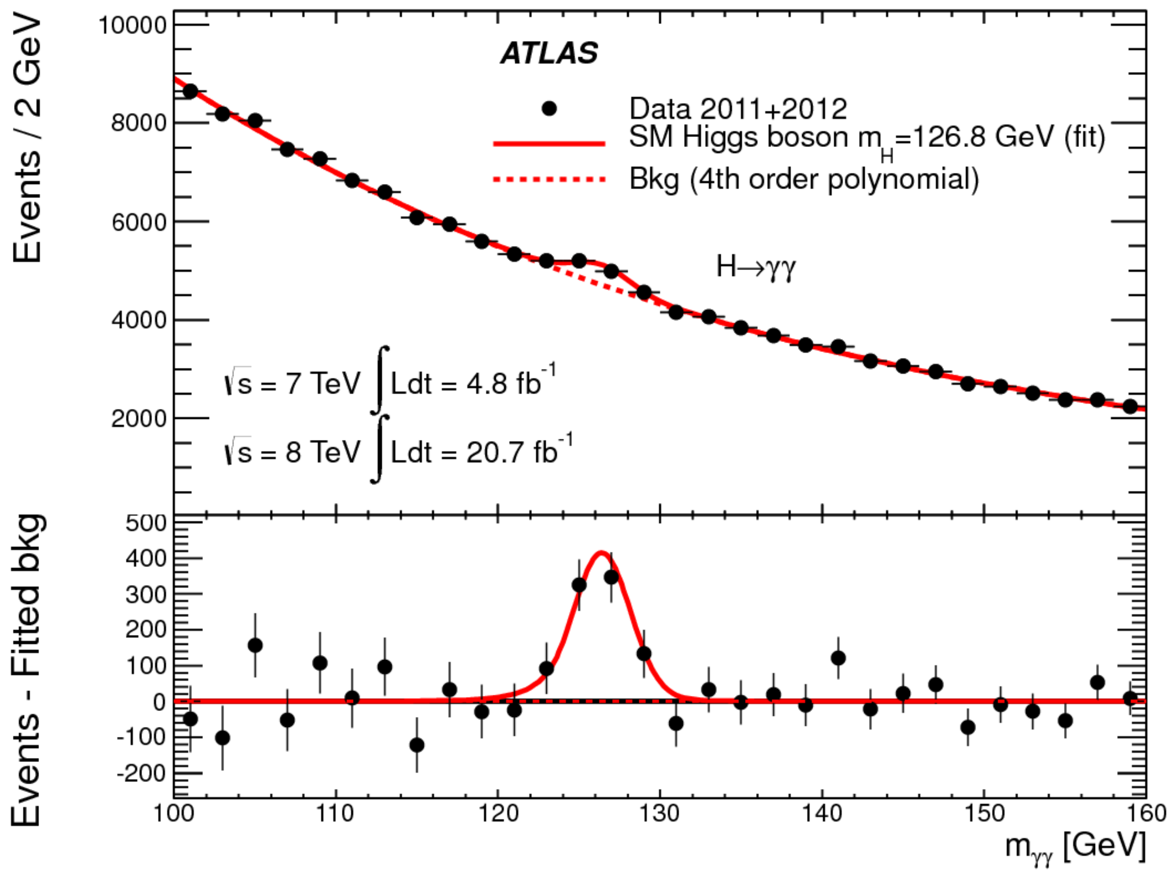
Muon beams
Unstable nuclei

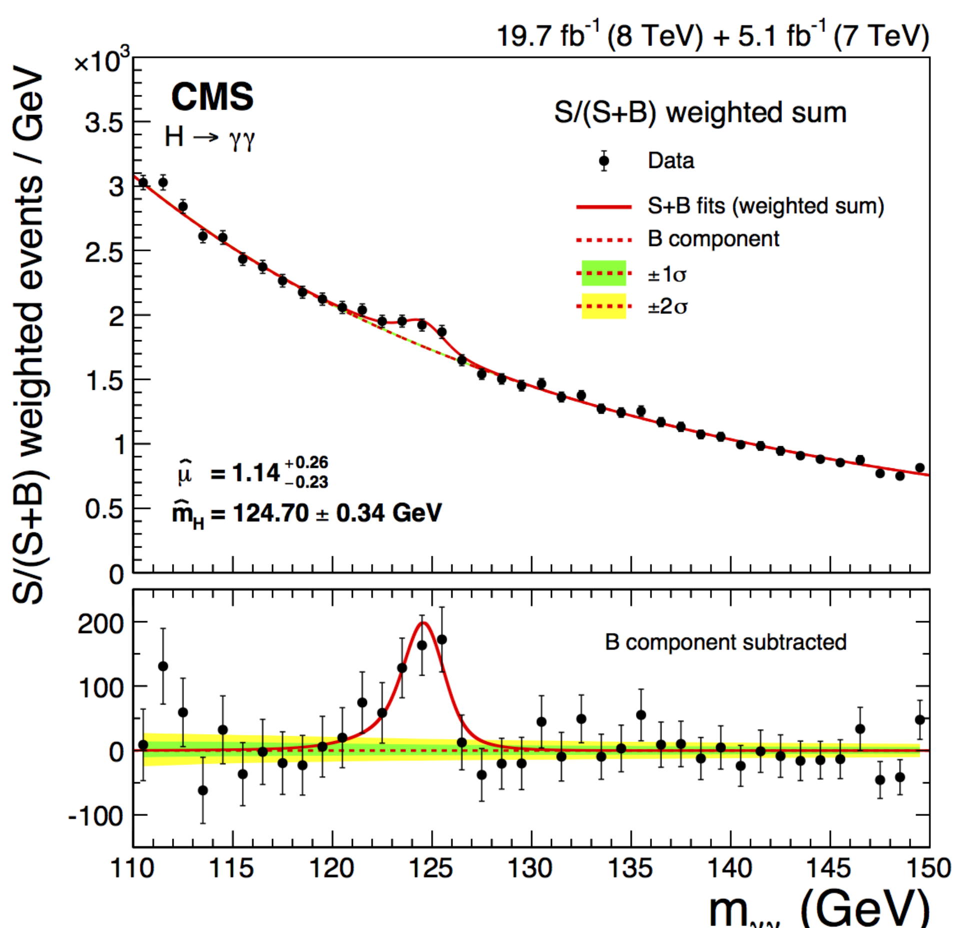
Cheap

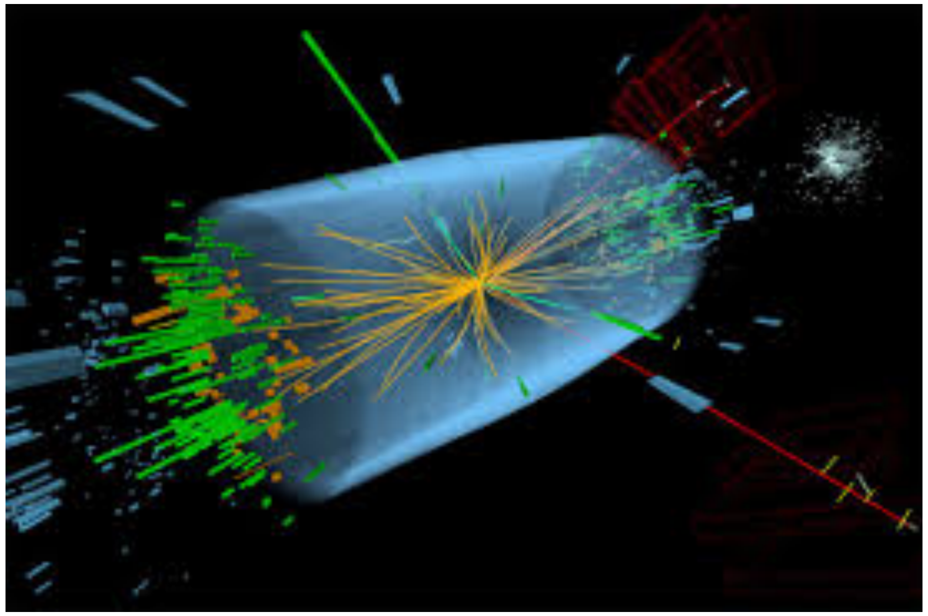
Hadron accelerators aren't known for being cheap

4th July 2012…

Brout-Englert-Higgs







1. What's after the Higgs?

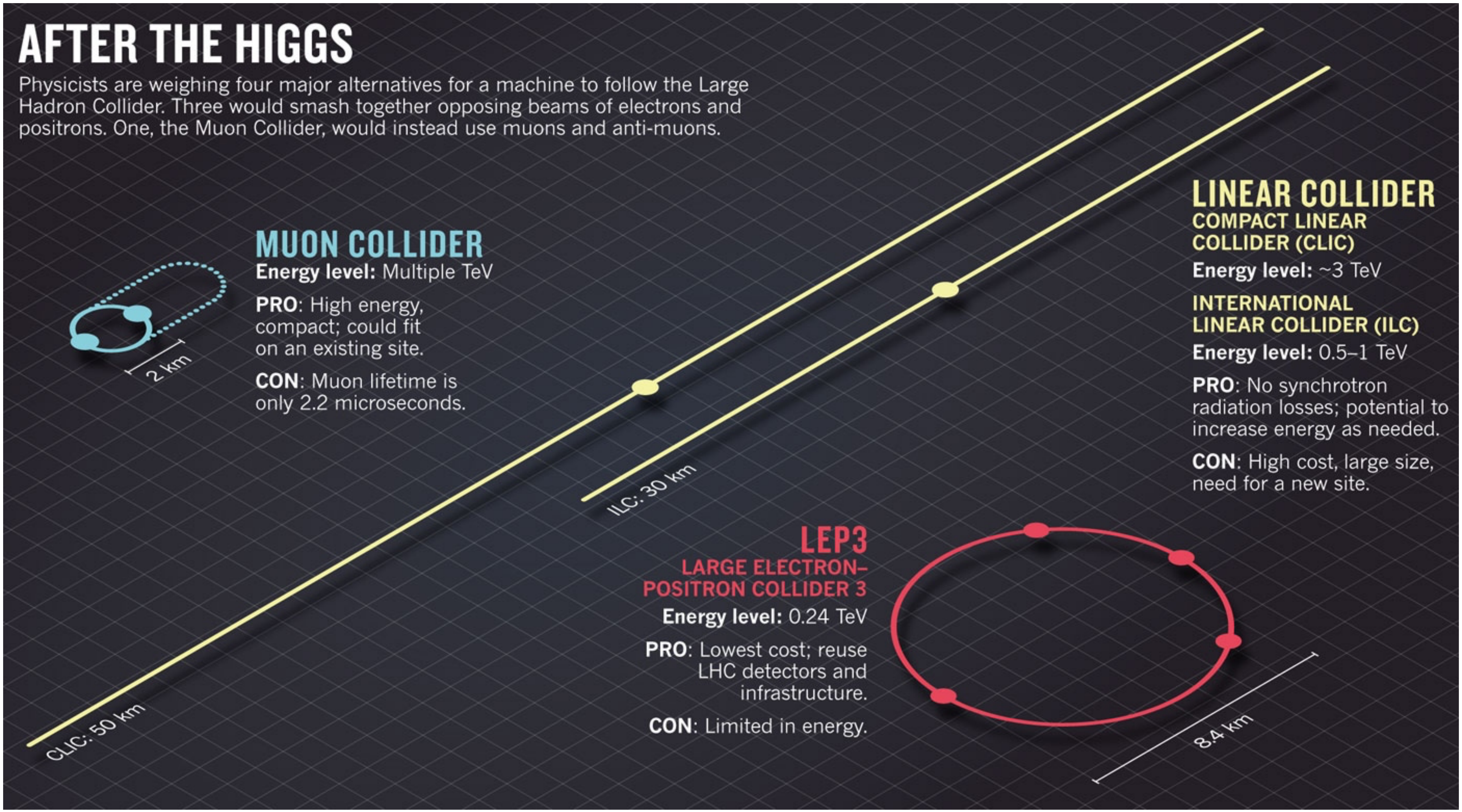
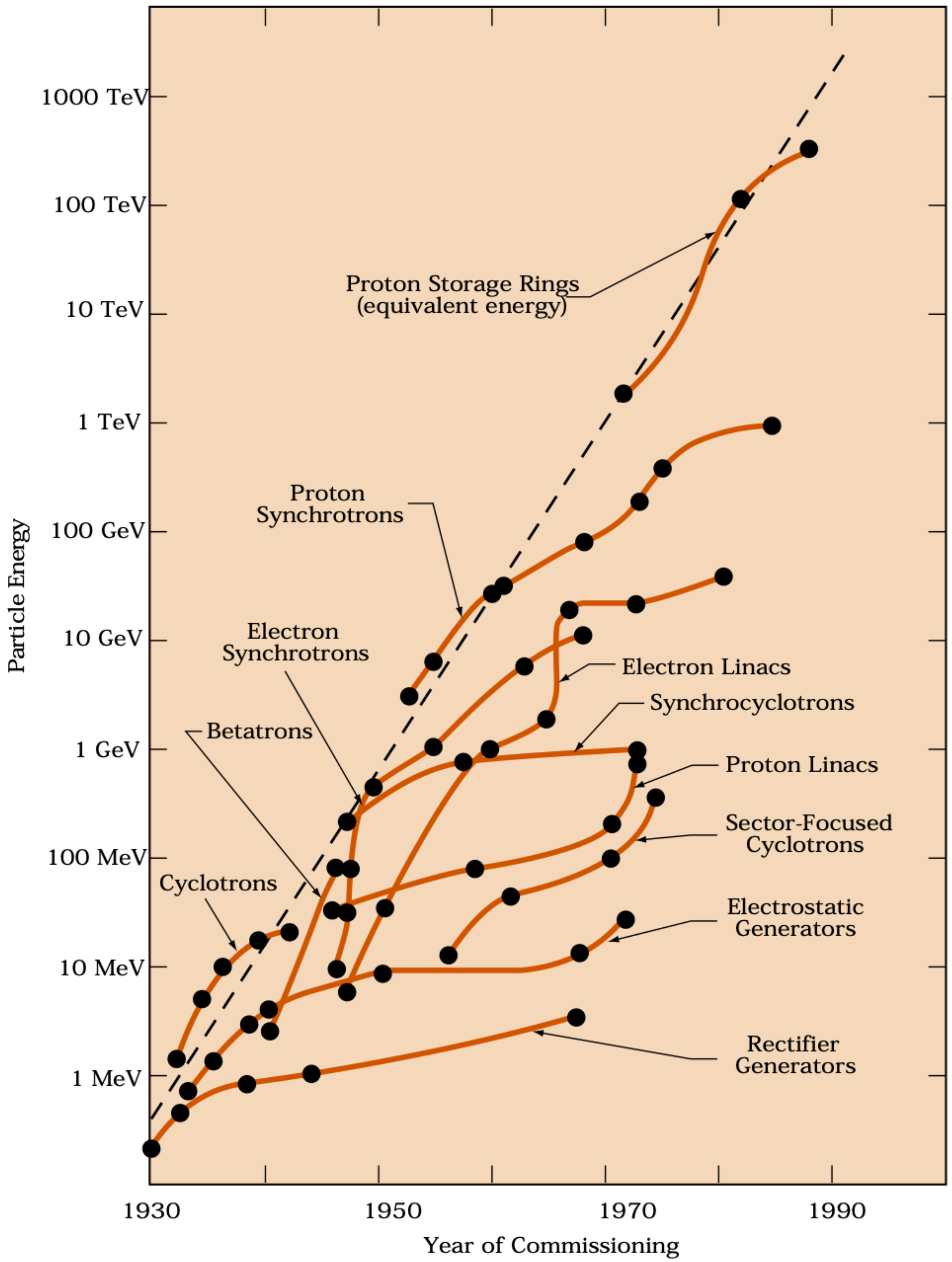


Image from nature.com, 2012. NB. nowadays the FCC is being studied not LEP3



‘Livingston plot’

M. Stanley Livingston:

advances in accelerator technology increase in energy record by **a factor of 10 every six years.**

Image: http://www.slac.stanford.edu/pubs/beamline/27/1/27-1-panofsky.pdf

Muon accelerators

- Why muons?

$$m_\mu = 105.6 \qquad m_e = 0.511$$

$m_\mu =$

Synchrotron radiation power

$$P \propto \gamma^4$$

$$200^4 = 1.6 \times 10^9$$

PHYSICS AT THE FARM: DISCOVERY OF THE MUON.

Muon accelerators

Muon collider

- Energy frontier:
  - Using a point particle means all energy goes into collision
  - Strong coupling to Higgs
- But:
  - They are *tertiary* particles $p \rightarrow \pi \rightarrow \mu + \bar{\nu}_\mu$
  - Large beams (large energy spread & emittance)
  - Short lifetime (2.2 usec)

What are the steps…?

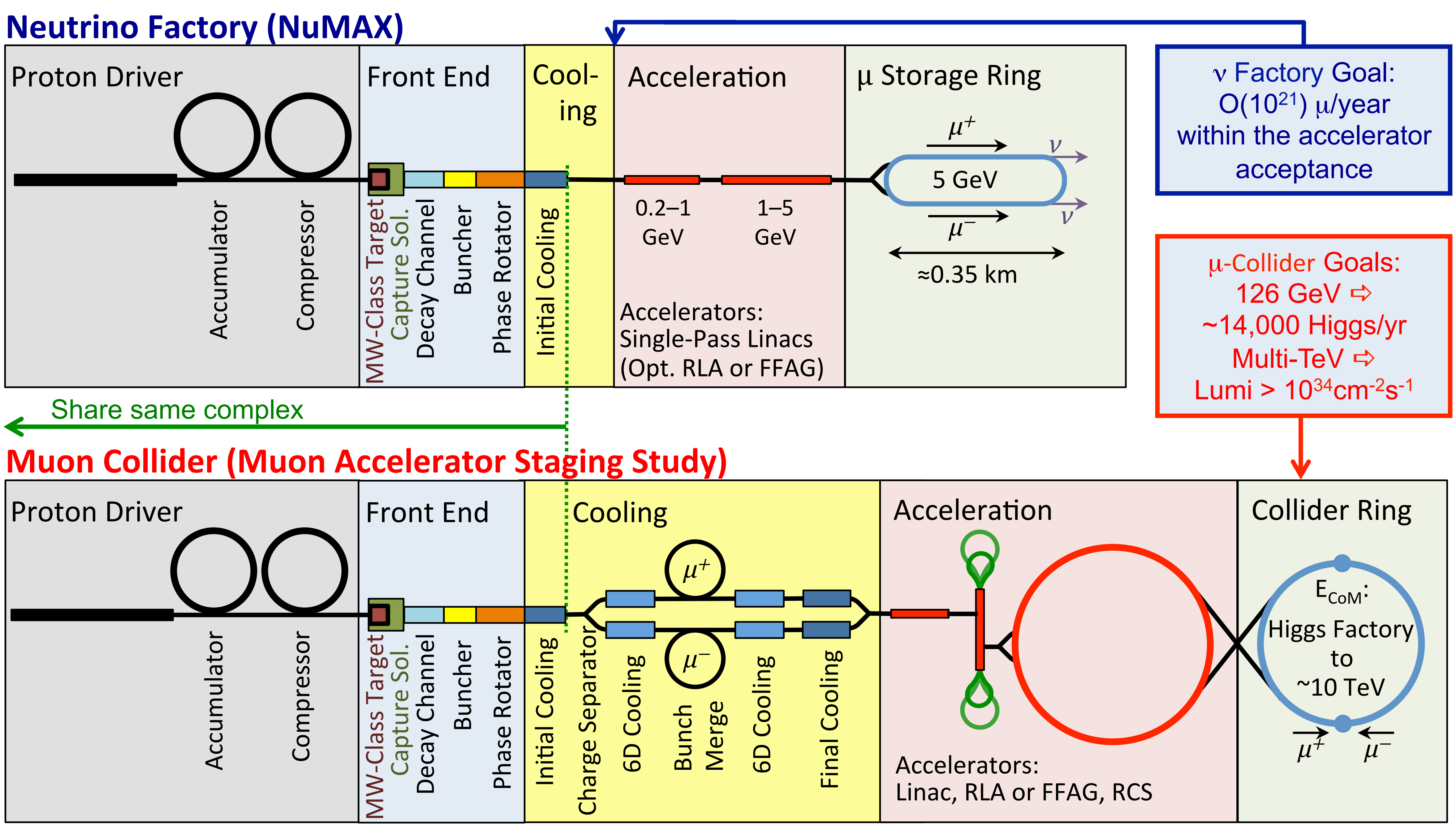


Image: from the US muon accelerator programme website

Comparison & challenges

	Neutrino Factory	Muon Collider
Transverse emittance	large	modest
Longitudinal emittance	large	3× higher
Energy	5–10 GeV	high
Allowed loss	some	low
Allowed emittance growth	some	low
Beam current	modest	high

Table from J. S. Berg, FFAG'14

Medical Applications

Medical applications

- Isotope production
- BNCT
- Proton therapy

Radioisotope Production

using p, d, 3He, 4He beams

p, d, 3He, 4He beams

Isotopes used for PET, SPECT (gamma) and Brachytherapy etc…

TABLE 2.1. THE RADIOISOTOPES THAT HAVE BEEN USED AS TRACERS IN THE PHYSICAL AND BIOLOGICAL SCIENCES

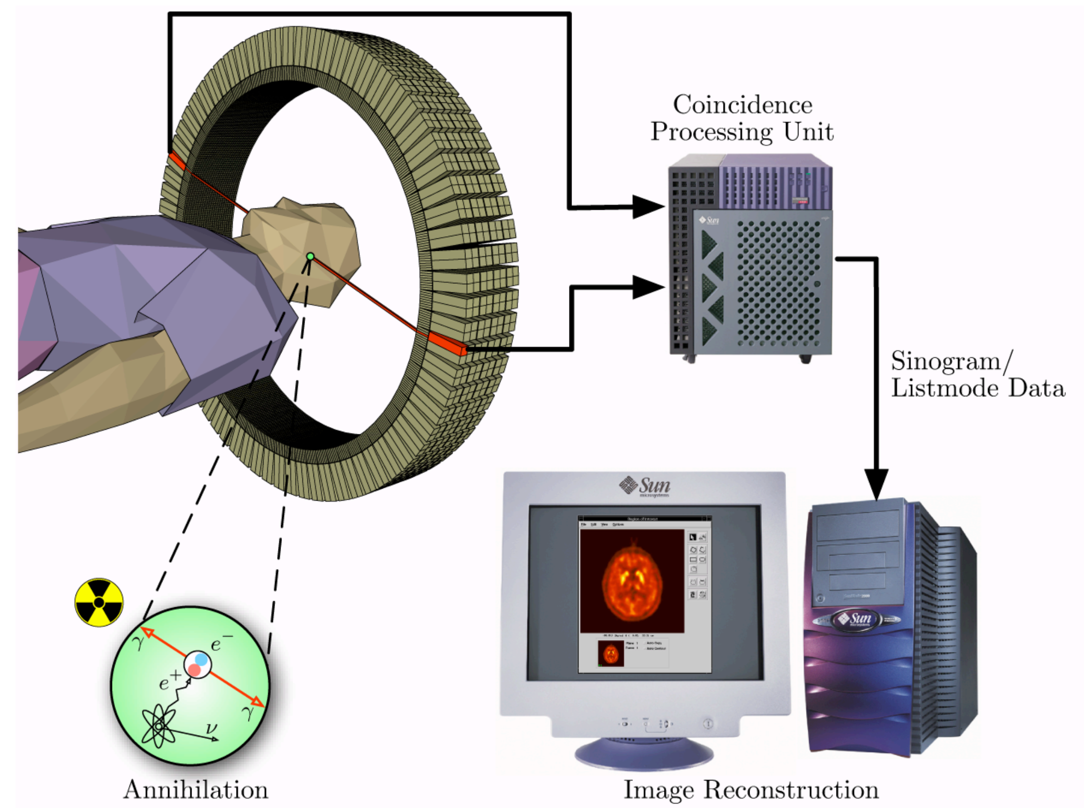
Isotope	Isotope	Isotope
Actinium-225	**Fluorine-18**	**Oxygen-15**
Arsenic-73	**Gallium-67**	**Palladium-103**
Arsenic-74	**Germanium-68**	**Sodium-22**
Astatine-211	Indium-110	**Strontium-82**
Beryllium-7	**Indium-111**	Technetium-94m
Bismuth-213	Indium-114m	**Thallium-201**
Bromine-75	Iodine-120g	Tungsten-178
Bromine-76	Iodine-121	Vanadium-48
Bromine-77	**Iodine-123**	Xenon-122
Cadmium-109	**Iodine-124**	Xenon-127
Carbon-11	Iron-52	**Yttrium-86**
Chlorine-34m	Iron-55	Yttrium-88
Cobalt-55	**Krypton-81m**	Zinc-62
Cobalt-57	Lead-201	Zinc-63
Copper-61	Lead-203	Zirconium-89
Copper-64	Mercury-195m	
Copper-67	**Nitrogen-13**	

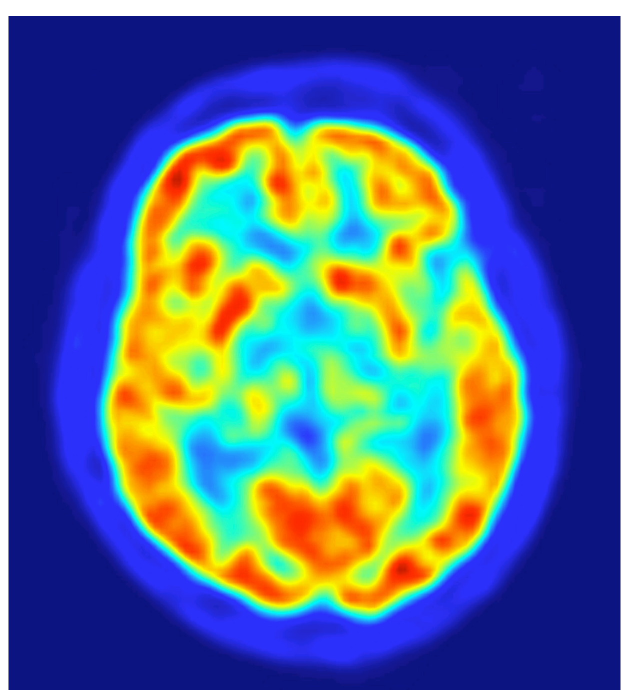
Radioisotope Production

Accelerators (compact cyclotrons or linacs) are used to produce radio-isotopes for medical imaging.

7-11MeV protons for short-lived isotopes for imaging

70-100MeV or higher for longer lived isotopes



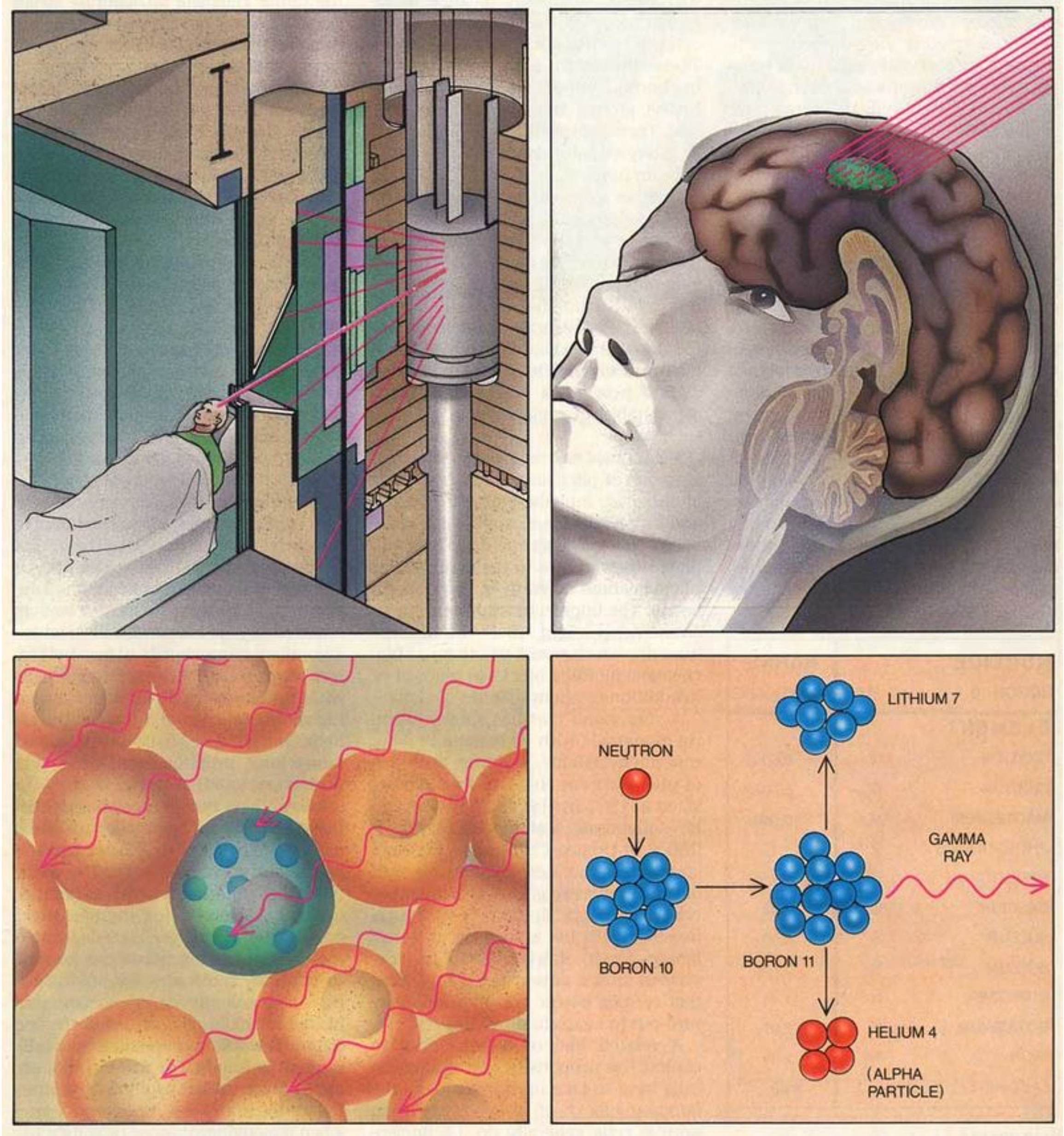


Positron emission tomography (PET) uses Fluorine-18, half life of ~110 min

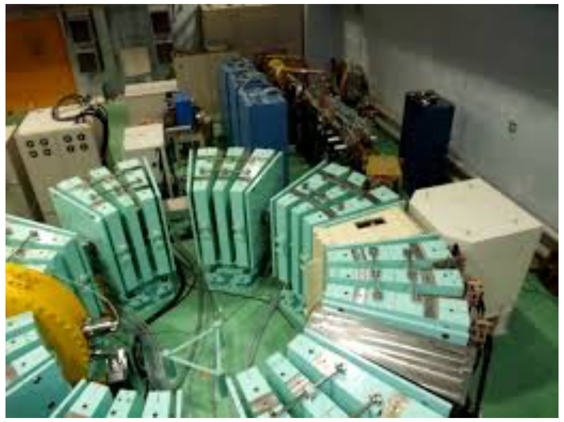
BNCT -Boron Neutron Capture Therapy

$^{10}B + n_{th} \rightarrow [^{11}B]^* \rightarrow \alpha + {}^{7}Li + 2.31$ MeV

- Deliver Boron-10 to target area
- Irradiate with source of neutrons
- Forms Boron-10
- Releases prompt radiation (alpha, Li) to destroy cells



Large neutron flux
> 1x10E09 n/cm2/sec at patient



Idea:
use energy
recovery system

ERIT at KURRI (See. Mori, hadron.kek.jp/FFAG/FFAG05_HP/material/7th/FFAG-ERIT.pdf

Cancer treatment

Linac

Foil to produce x-rays

Collimation system

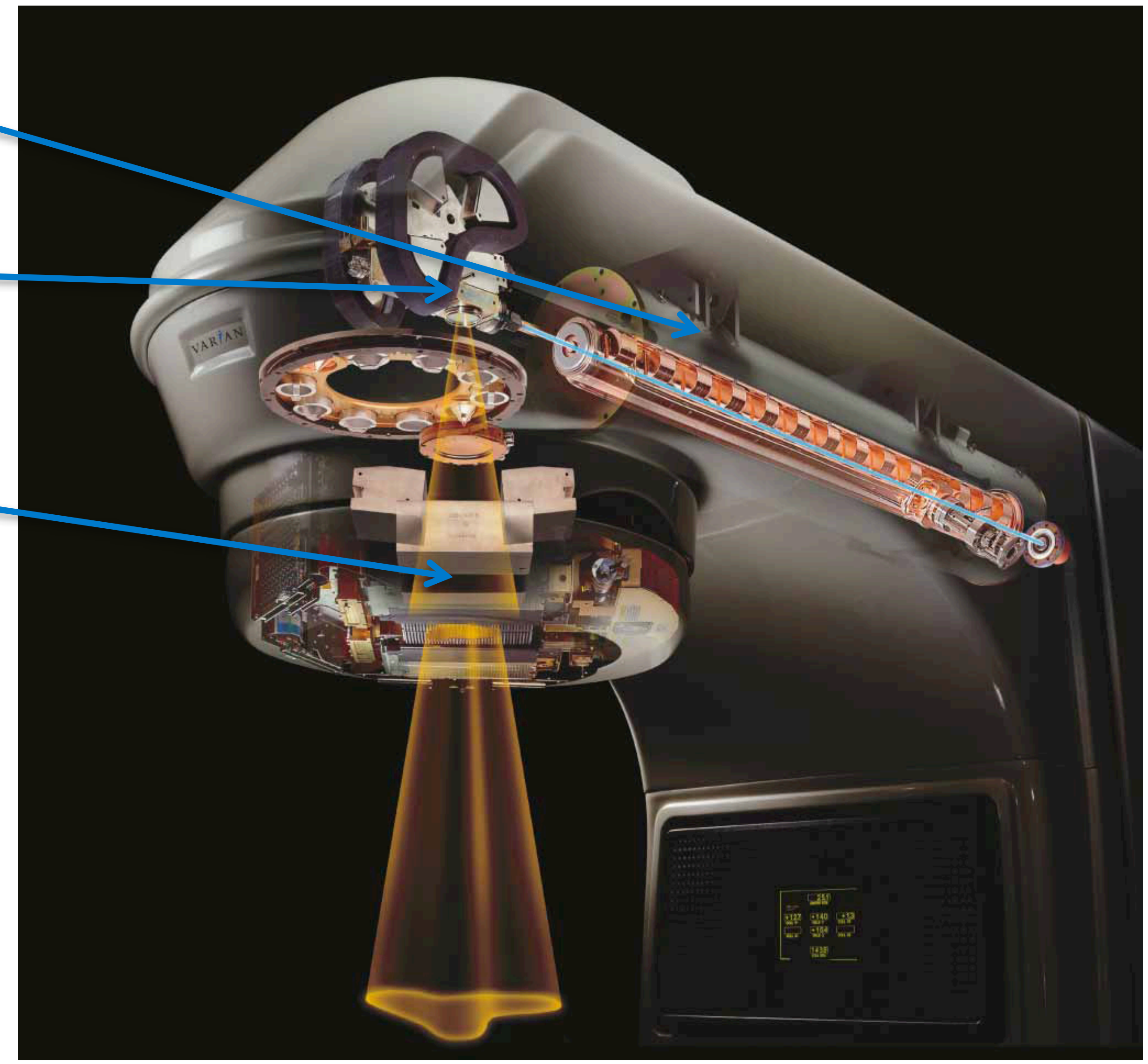


Image: copyright Varian medical systems

Radiation is used in around 50% of all treatment cases

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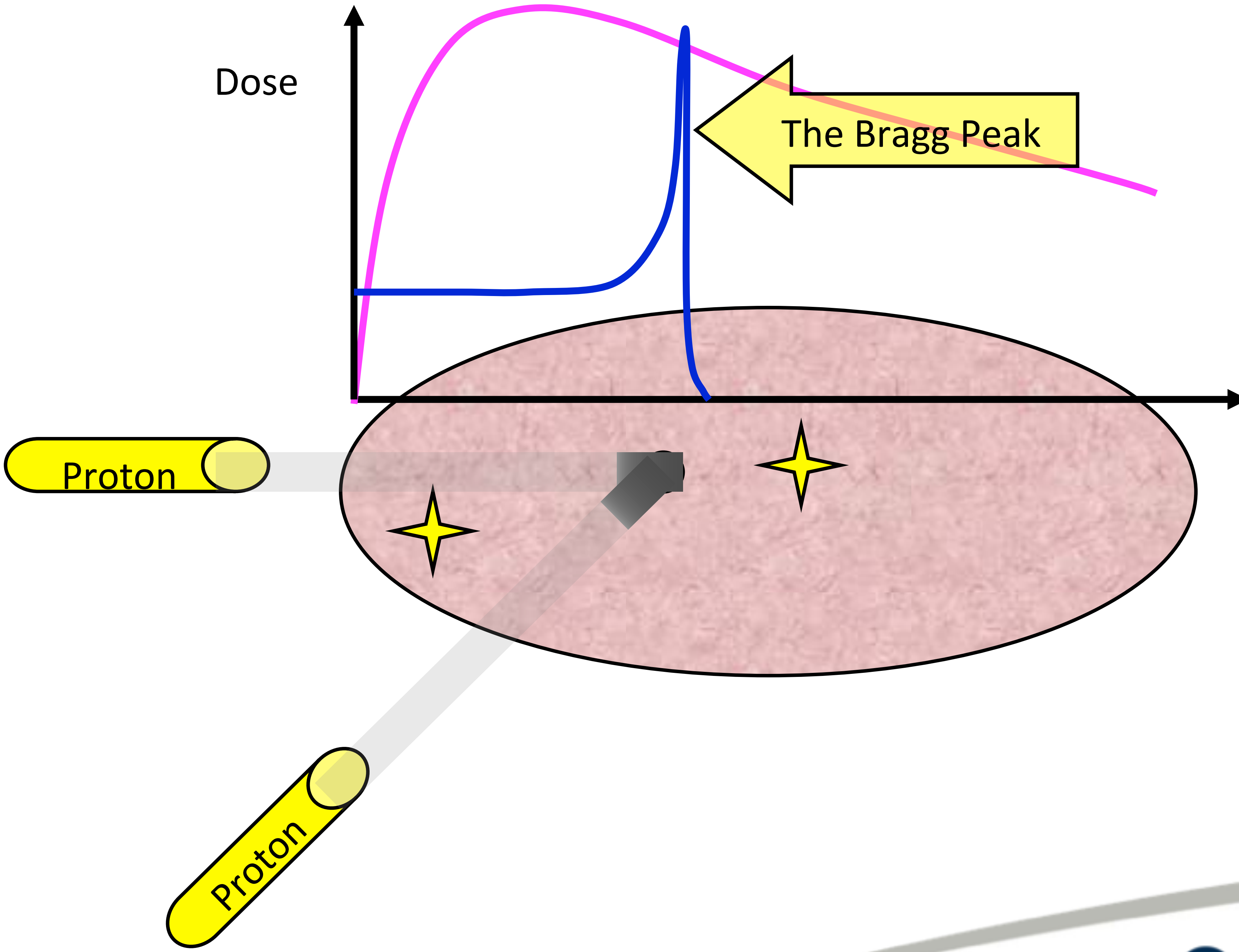
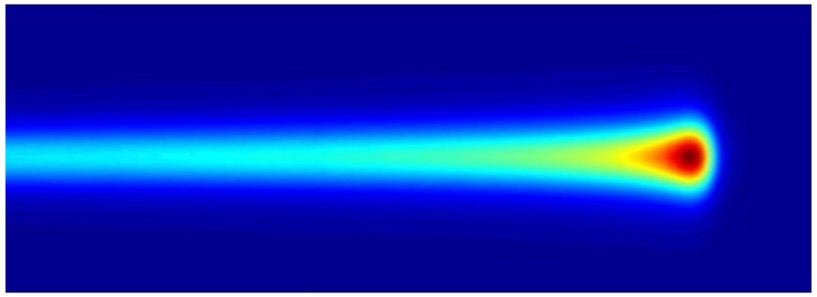
Can we only use X-rays?



Energy loss in materials



The relativistic version of the formula reads:

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \boxed{\frac{nz^2}{\beta^2}} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right) - \beta^2\right]$$

where

β $= v / c$

v velocity of the particle

E energy of the particle

x distance travelled by the particle

c speed of light

$z\,e$ particle charge

e charge of the electron

m_e rest mass of the electron

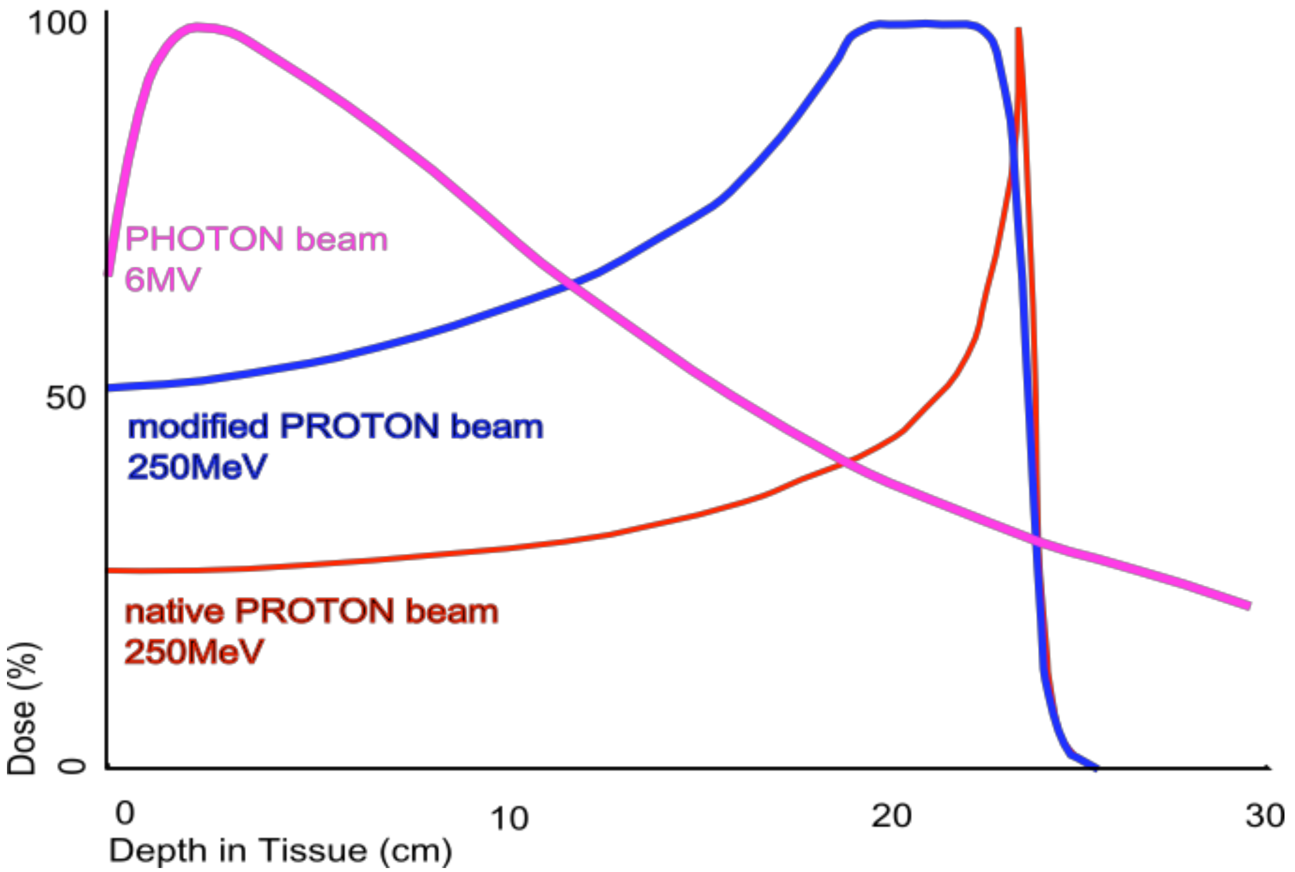
n electron density of the target

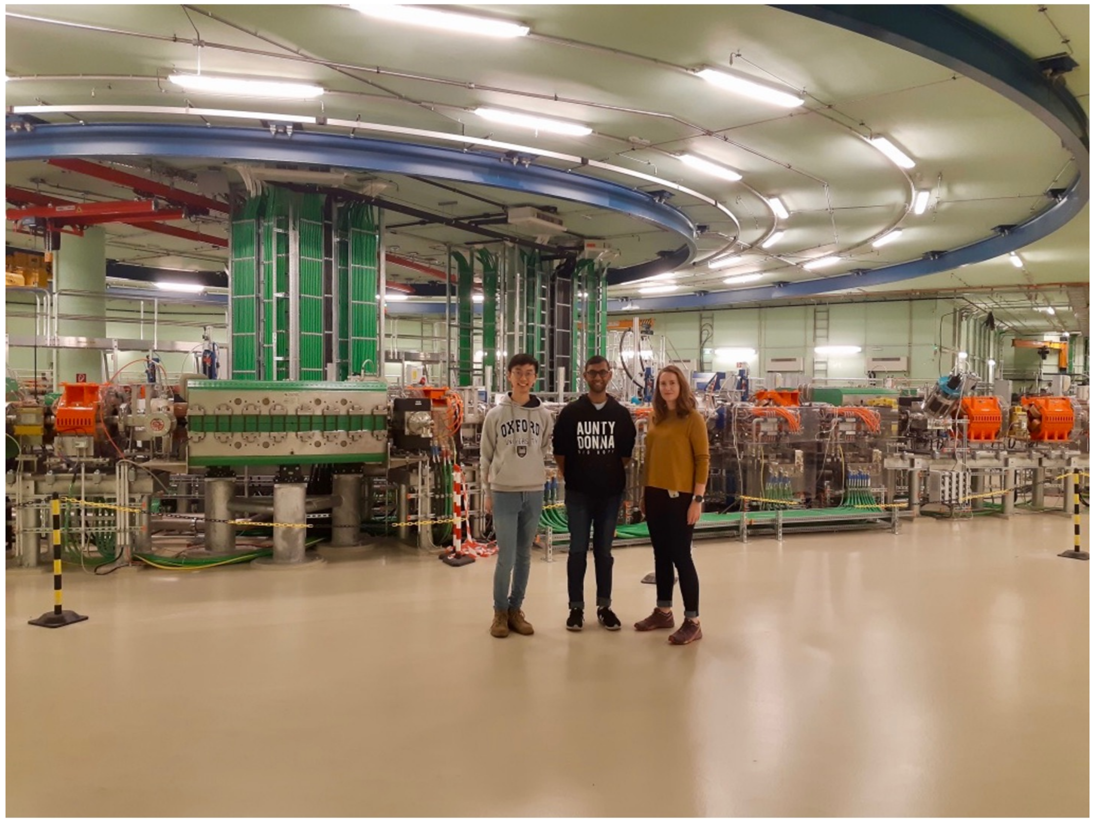
I mean excitation potential of the target

ε_0 vacuum permittivity

High speed -> small energy loss
Low speed -> high energy loss

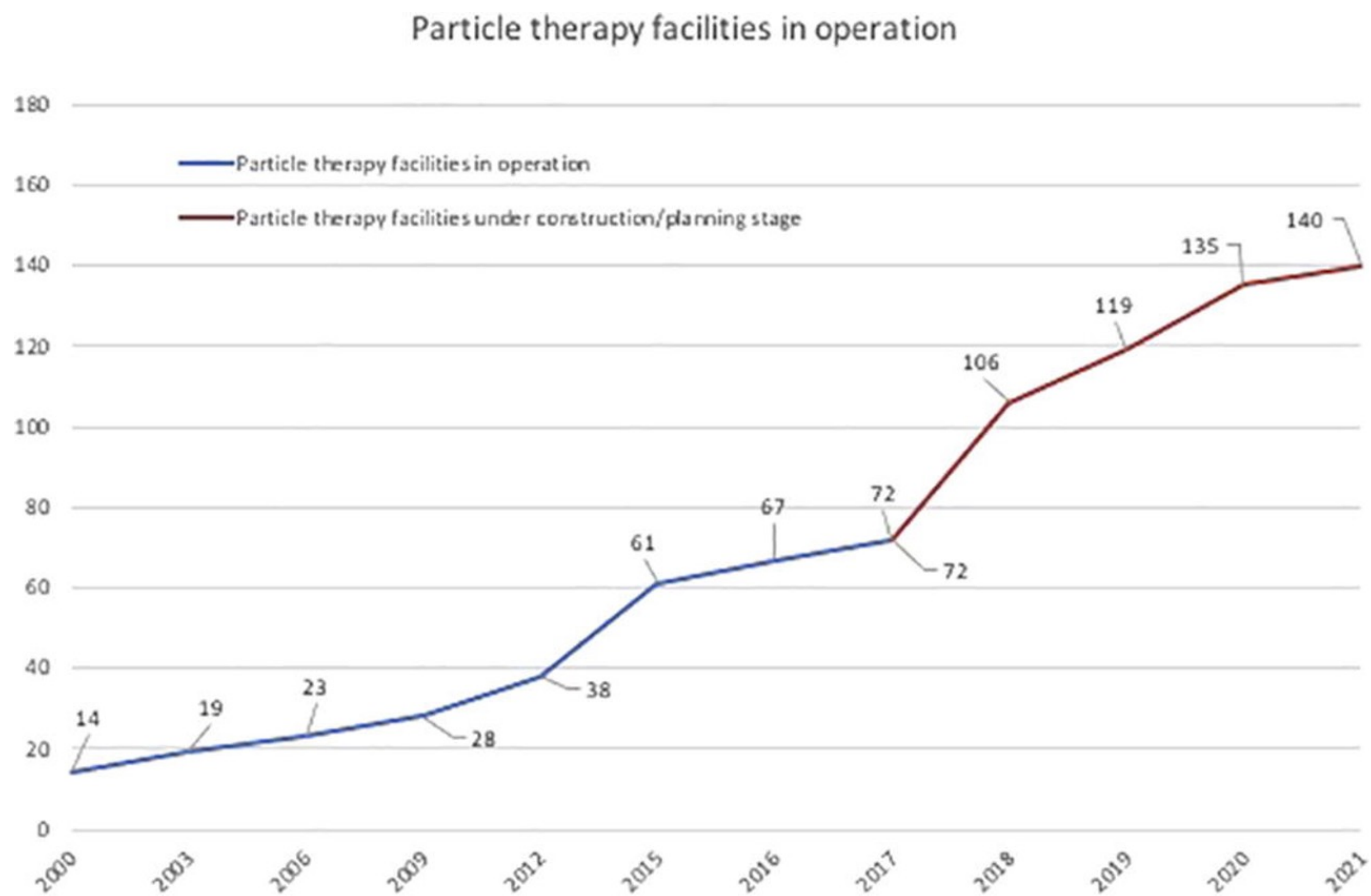
Hadron Therapy





Greater dose where needed
Less morbidity for healthy tissue
Less damage to vital organs

Hadron therapy facilities



http://www.ptcog.ch/index.php/facilities-in-operation

Another type of accelerator?

‘Modern’ Proton/ion therapy has seemingly conflicting requirements for the accelerator:

Size & cost

Rapid variable energy

Easy to operate & reliable

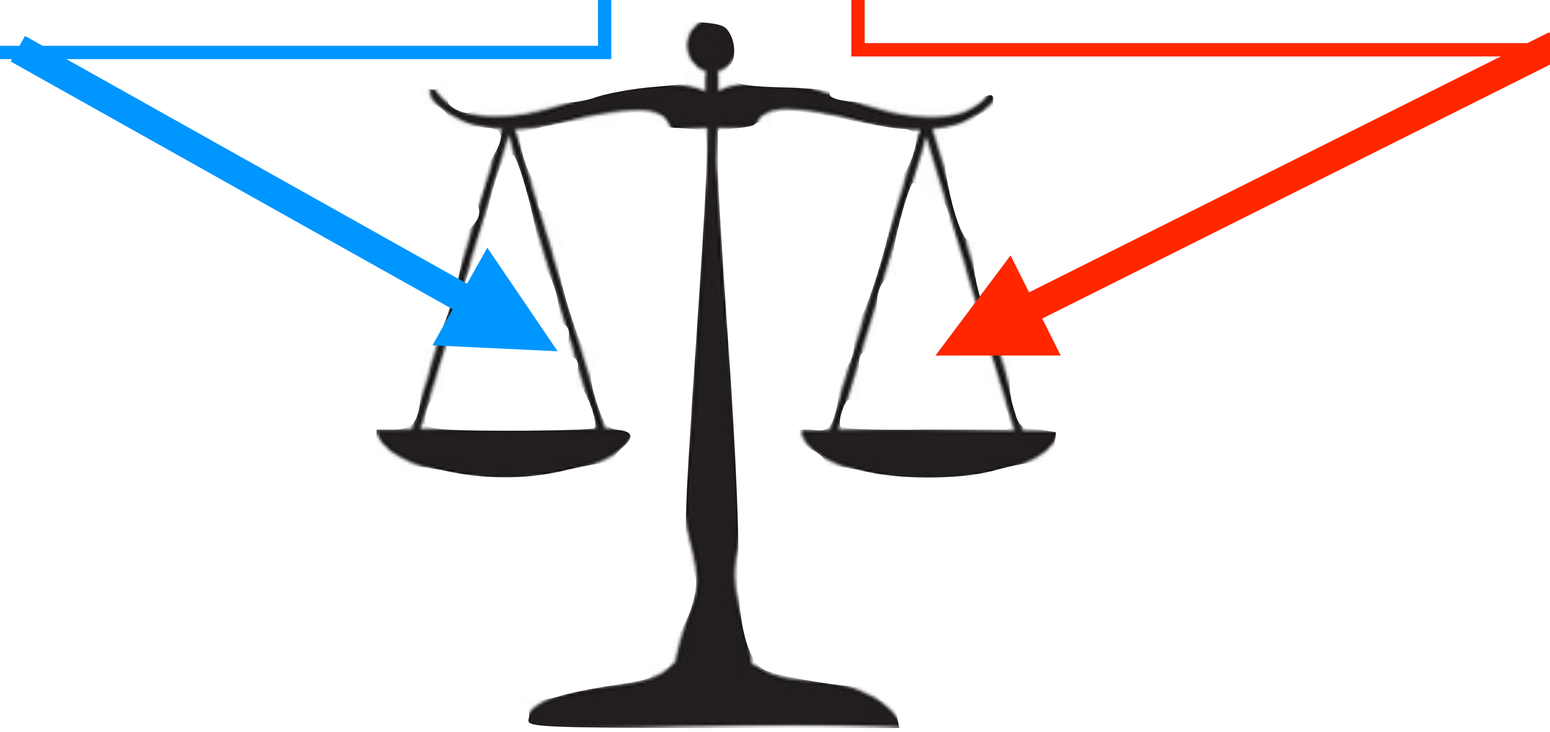
Relatively low intensity

Ability to deliver best treatment

Large range of energies

Precision required

Variation of intensity required



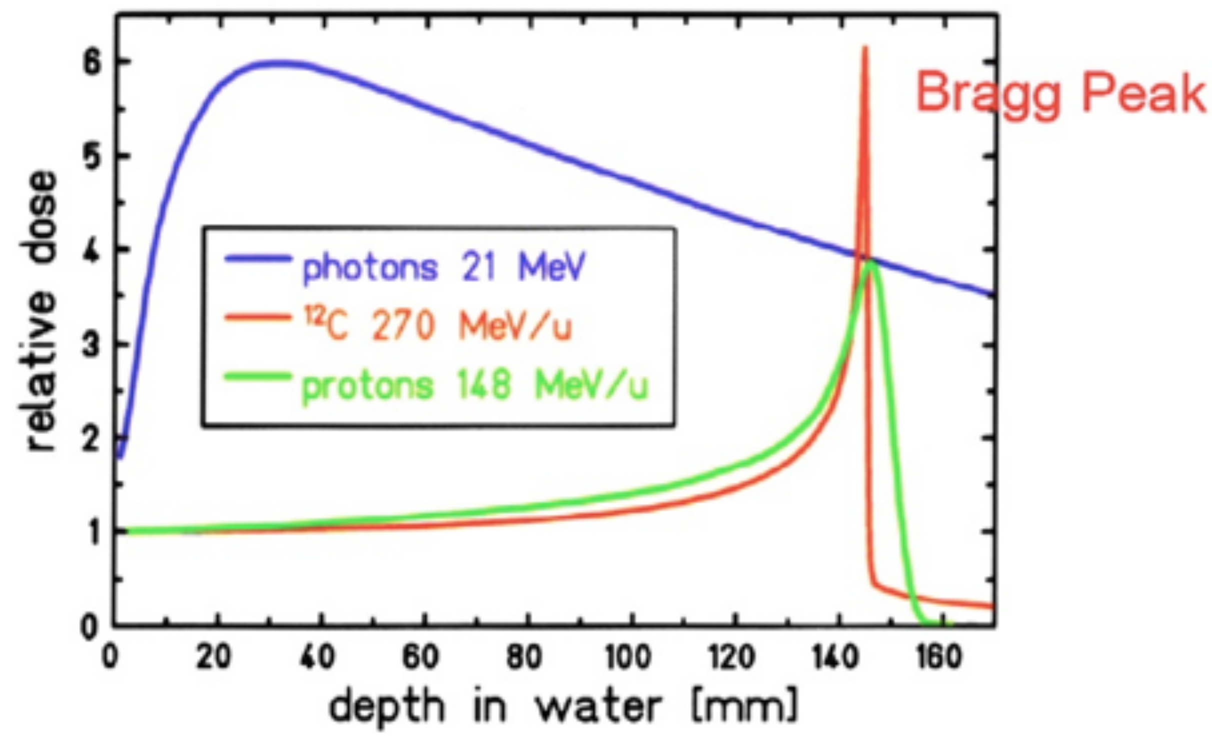
Another type of accelerator?

- Additional challenges still to be met:

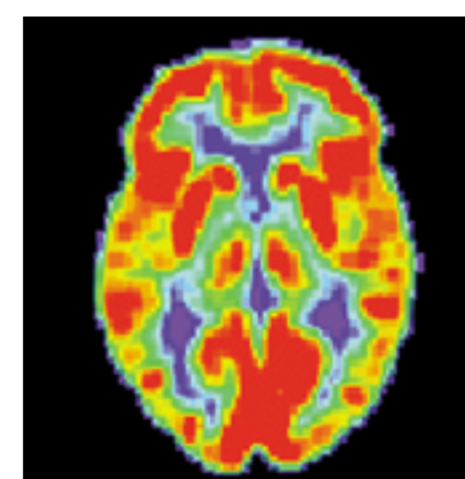
Image: GSI Heidelberg

How can we make smaller/ lighter/cheaper gantries?

- Particle species variation
- Online proton radiography



High intensity, compact sources for radioisotope production



High Power Applications

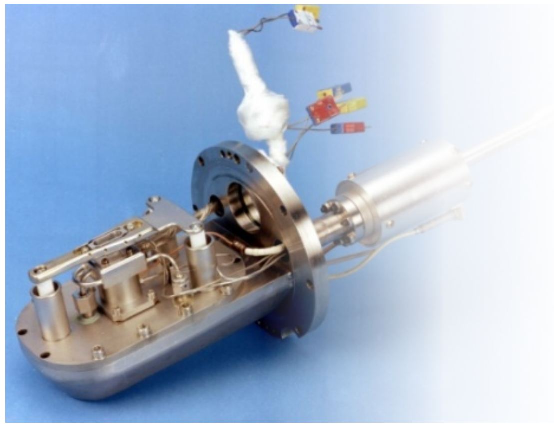
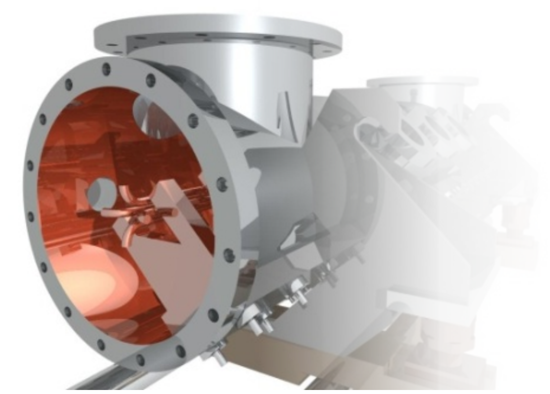
- ADSR
- (Isotope production - already covered)
- Space charge issues

Neutron Sources

(Wish Diffraction Animation)

https://player.vimeo.com/video/12555378

‘Neutrons tell you where atoms ***are*** and what atoms ***do***’

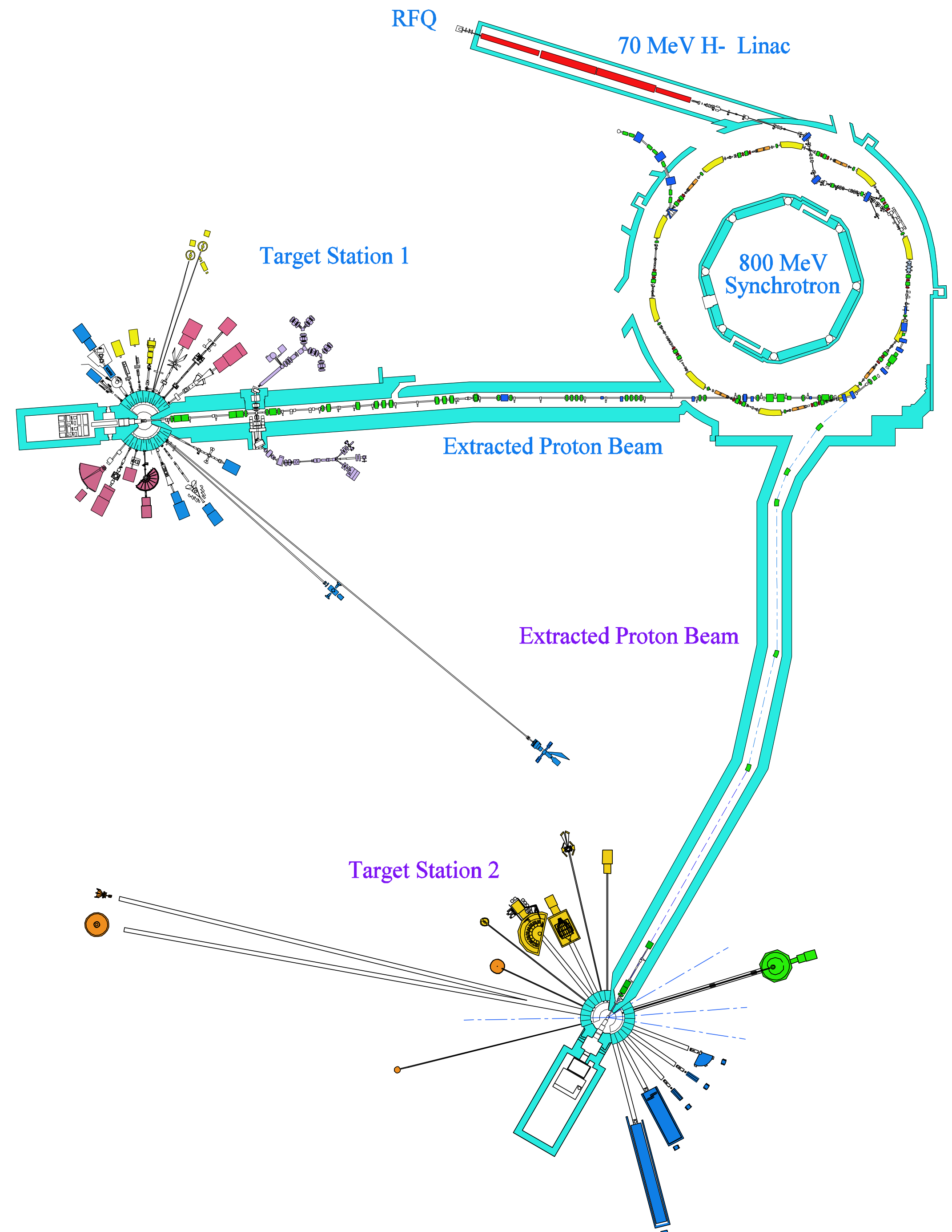




ISIS Accelerators and Targets

- H^- ion source (17 kV)
- 665 kV H^- RFQ
- 70 MeV H^- linac
- 800 MeV proton synchrotron
- Extracted proton beam lines
- Targets
- Moderators

Pulsed beam of 800 MeV
(84% speed of light) protons
at 50 Hz
Average beam current
is 230 muA (2.9×10^{13} ppp)

184 kW on target (148 kW to TS-1 at 40 pps, 36 kW to TS-2 at 10 pps).



Calculating beam power

Power = Work/time $$P = \frac{W}{T}$$

Work = force x distance $$W = Fd$$

Force on particle in an electric field $$F = qE$$

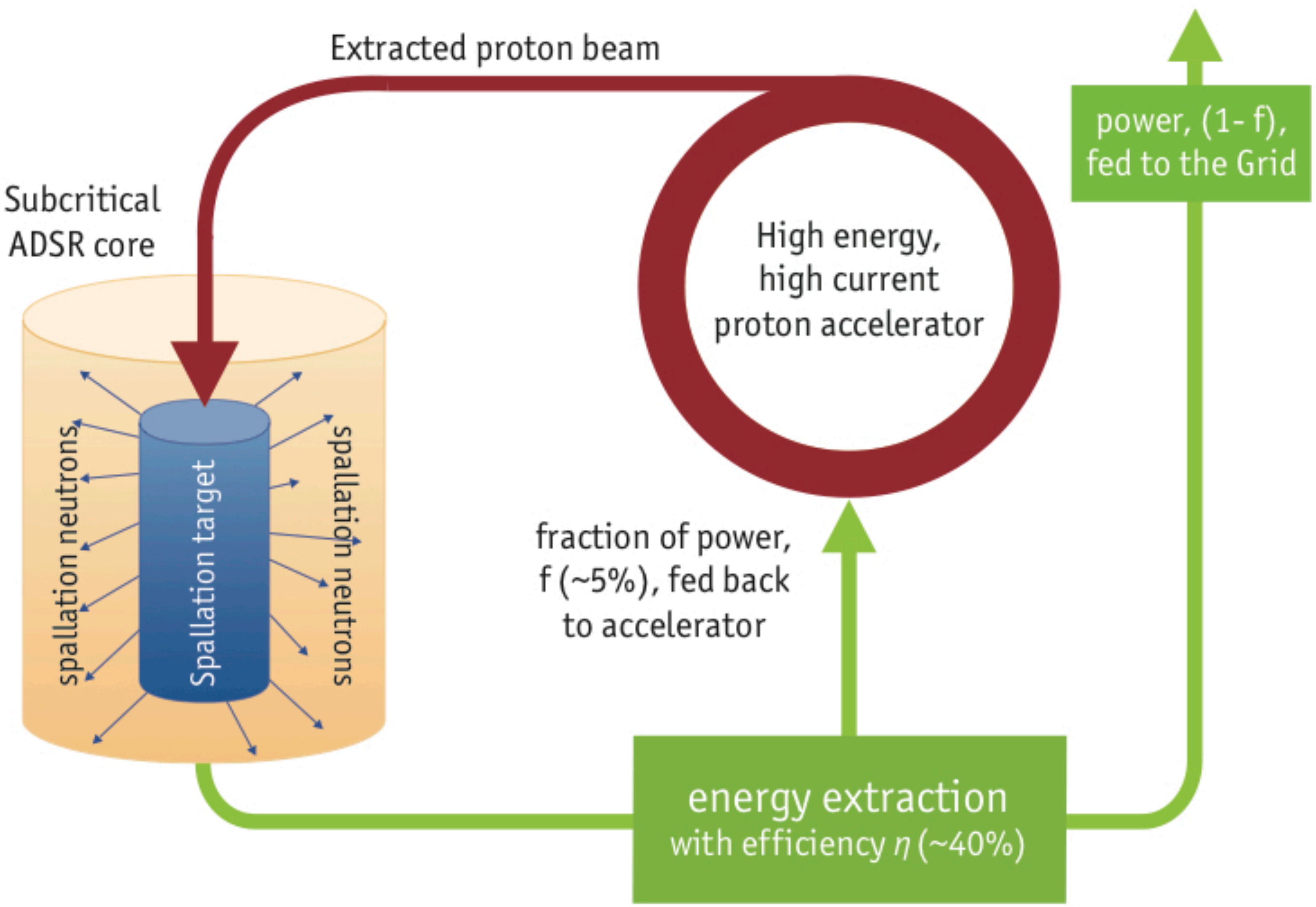
We know the electric field is (voltage/distance) and the protons (charge +1) have gained 800 MeV, so V=800MV.

Also know current = charge/time

$$P = 800[MV] \times 230[\mu A] = 184[kW]$$

ADS systems

Transmutation of nuclear waste isotopes or energy generation



Thorium

Major challenges for accelerator technology in terms of beam power (>10MW) and reliability

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Another possibility: muon transmutation, see Y. Mori, FFAG'14

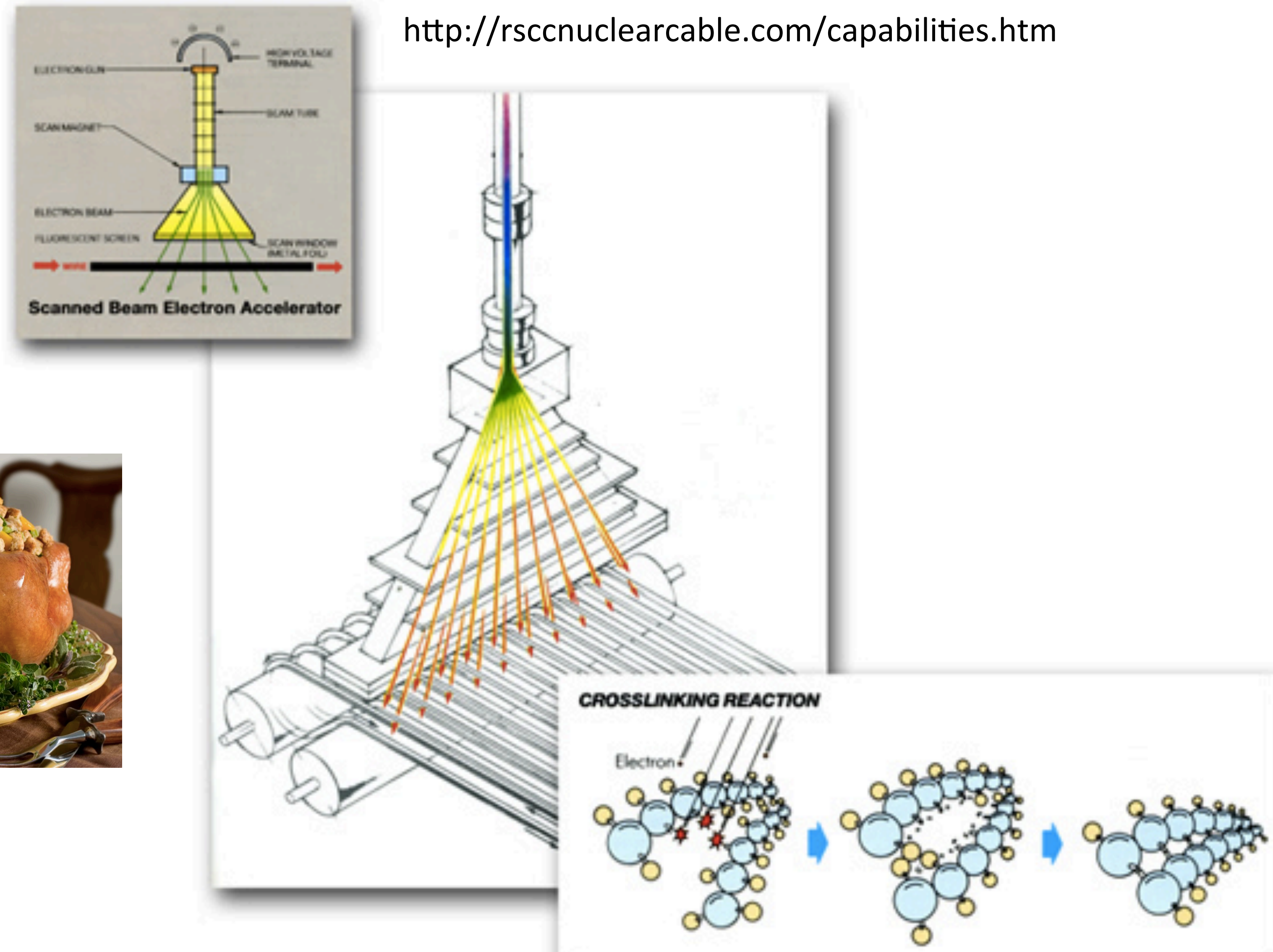
4. Cost effective accelerators?

Electron beam processing

In the US, potential markets for industrial electron beams total $50 billion per year.

33% Wire cable tubing
32% Ink curing
17% shrink film
7% service
5% tires
6% other

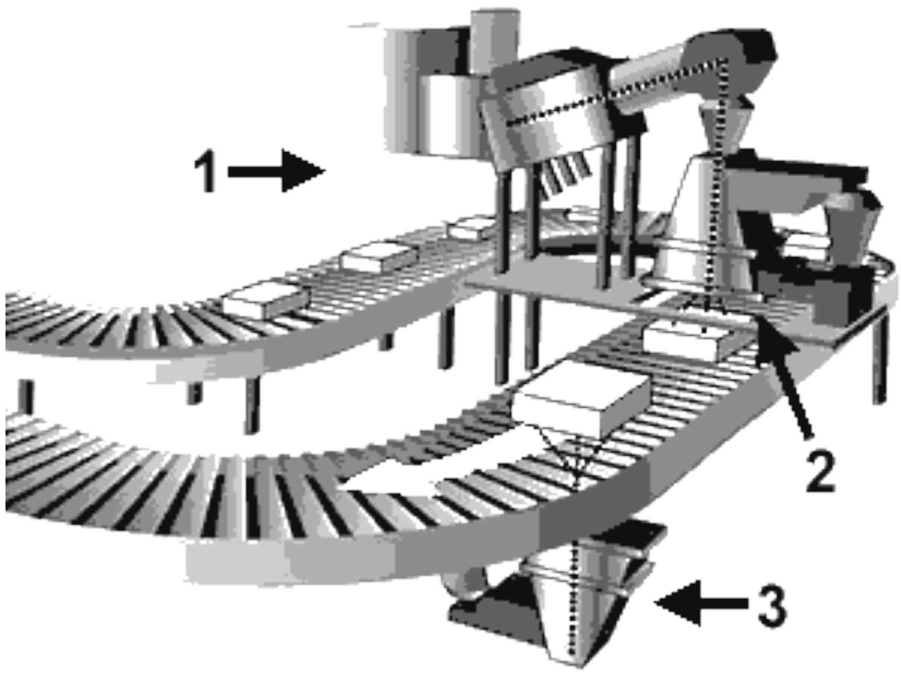
http://rsccnuclearcable.com/capabilities.htm



When polymers are cross-linked, can become:

- stable against heat,
- increased tensile strength, resistance to cracking
- heat shrinking properties etc

Food irradiation



'Cold pasteurisation' or 'electronic pasteurisation'
Uses electrons (from an accelerator) or X-rays produced using an accelerator.

The words 'irradiated' or 'treated with ionising radiation' must appear on the label packaging.

In the US all irradiated foods have this symbol

Foods authorised for irradiation in the EU:

Lower dose → Higher dose

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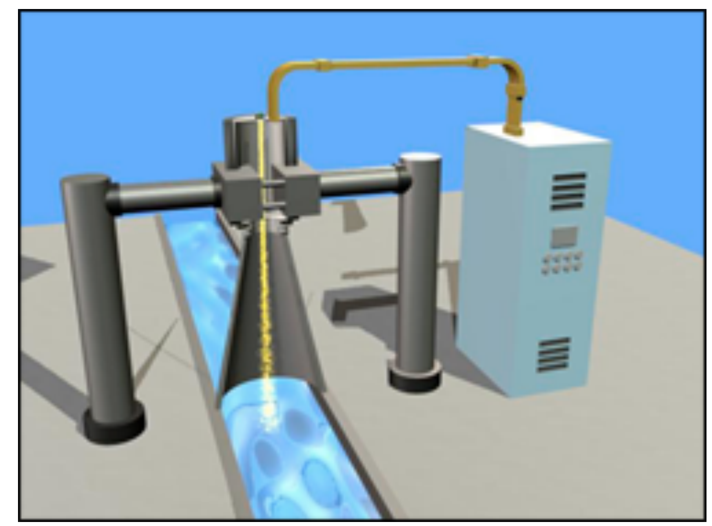
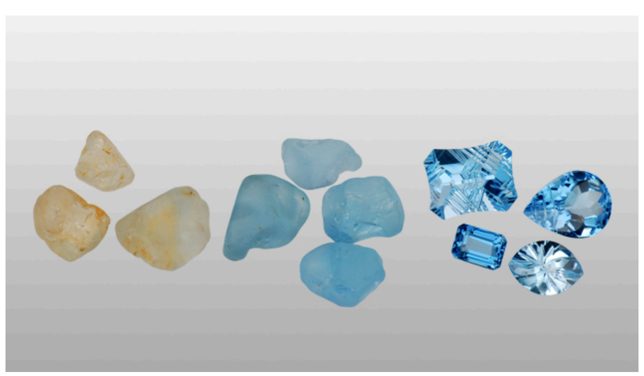
Other uses in industry…

Hardening surfaces of artificial joints
Removal of NO_x and SO_x from flue gas emissions
Scratch resistant furniture

Treating waste water or sewage
Purifying drinking water





Irradiating topaz and other gems with electron beams to change the colour

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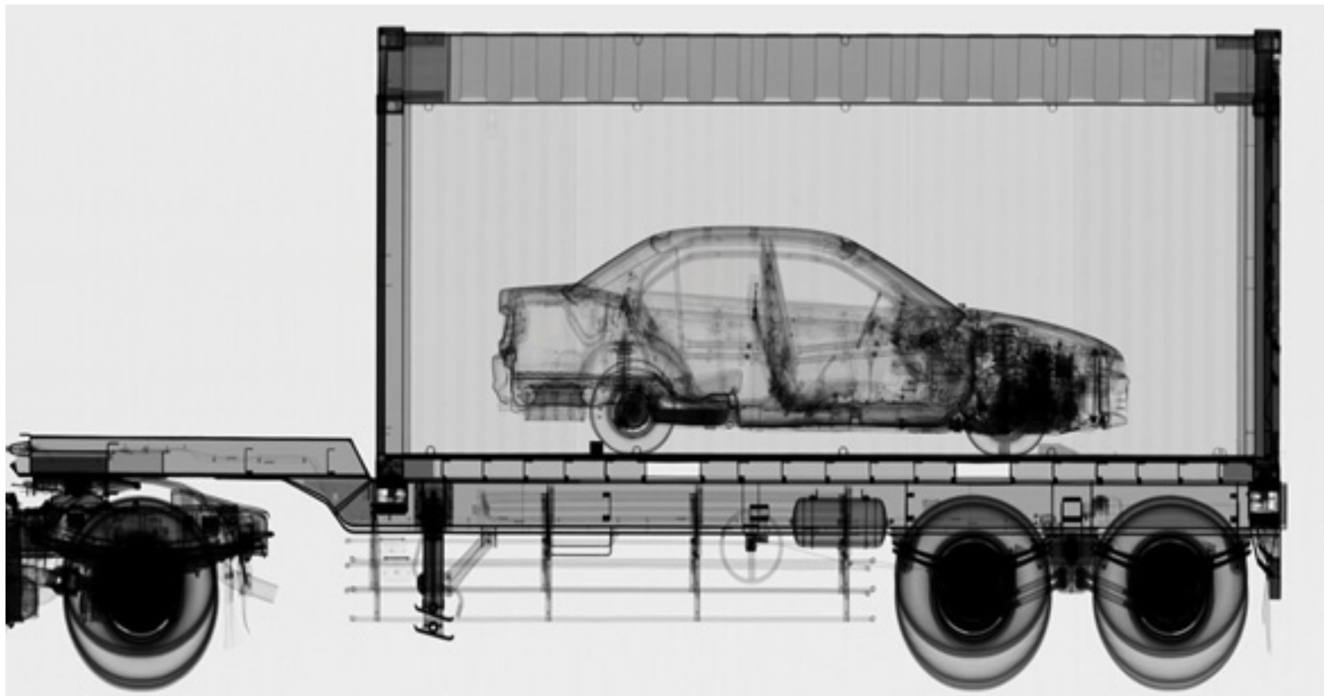
Cargo scanning



Cargo containers scanned at ports and border crossings

Accelerator-based sources of X-Rays can be far more penetrating (6MV) than Co-60 sources.

Container must be scanned in 30 seconds.

Image source: Varian medical systems

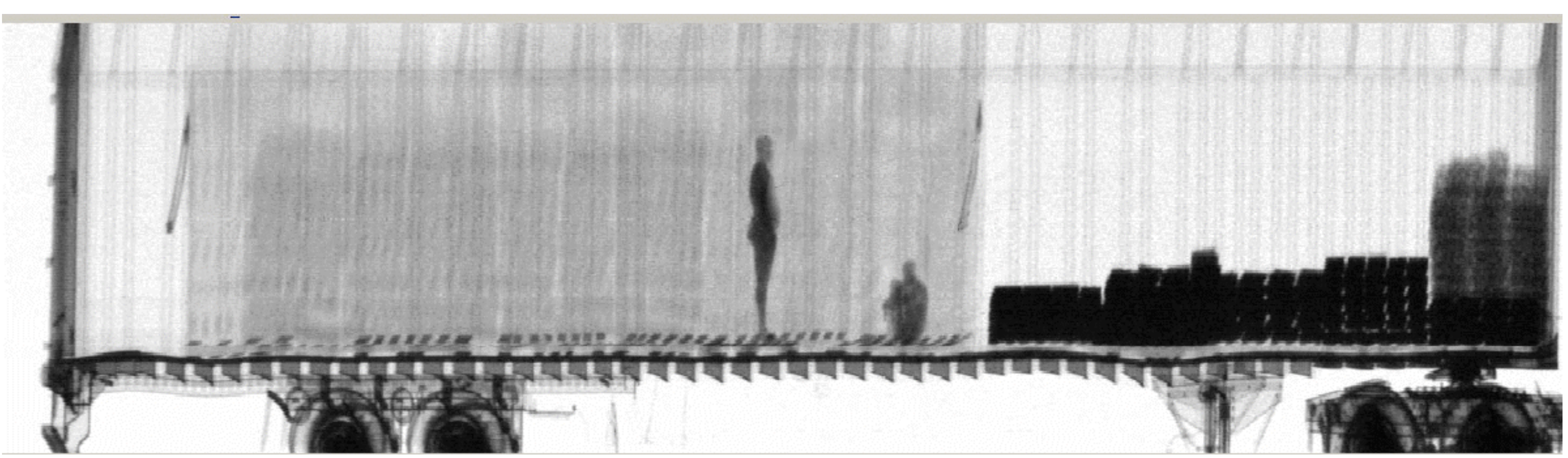


Image: dutch.euro

For FFAs, potential applications include:

- Proton drivers (ADSR, neutrons)
- Boron Neutron Capture Therapy
- Proton/carbon therapy & isotope production
- Emittance/Energy Recovery with Internal Target (ERIT)
- Return arcs on recirculating linac… FEL/other
- Muon or neutrino factory source
- + many more…

"A beam of the right particles with the right energy at the right intensity can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, package a Thanksgiving turkey or… discover the secrets of the universe."

– Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011