Introduction to FFAGs

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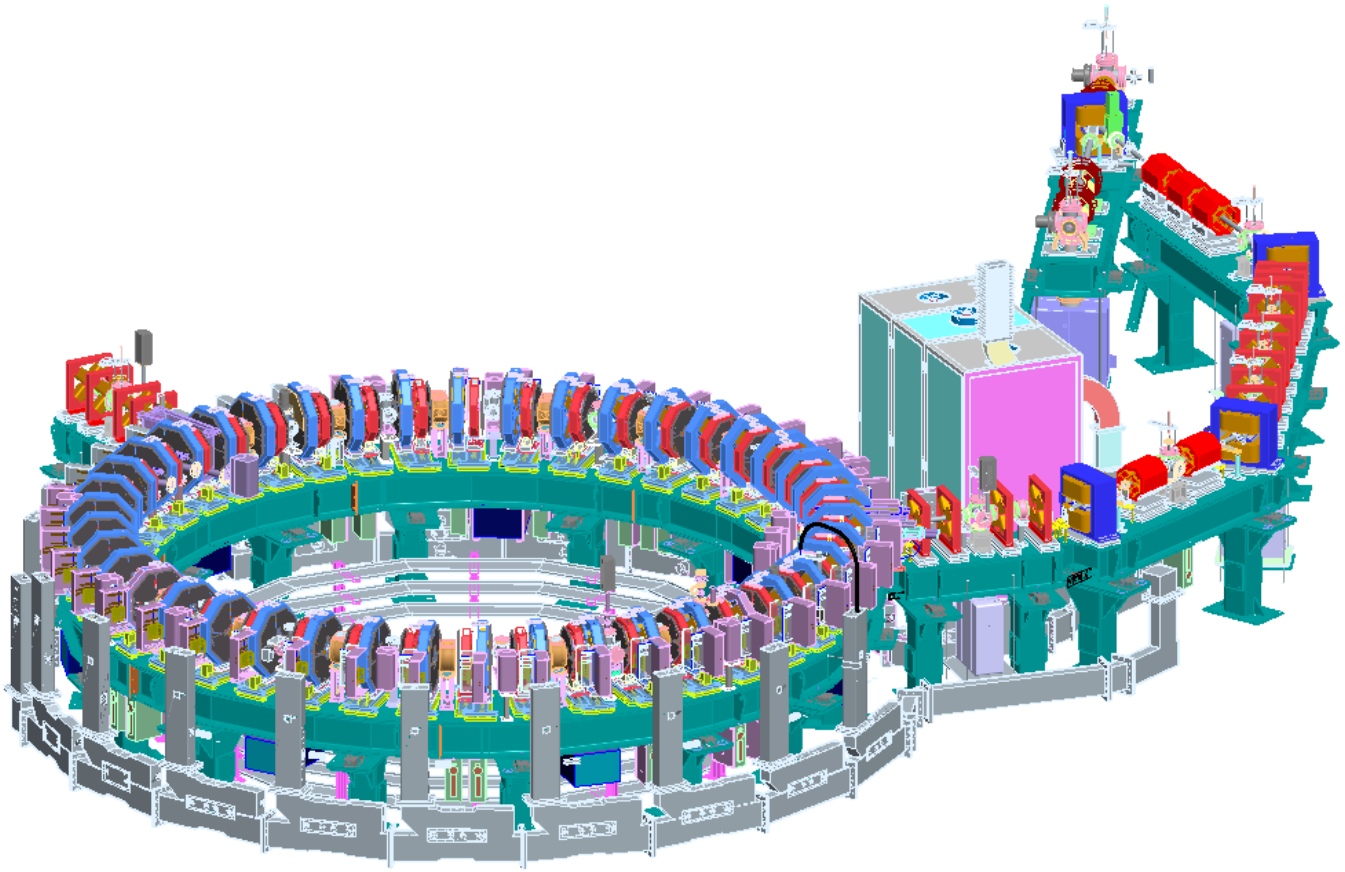


Outline

Focus on particle accelerators

- Introduction to accelerators
- Accelerator applications

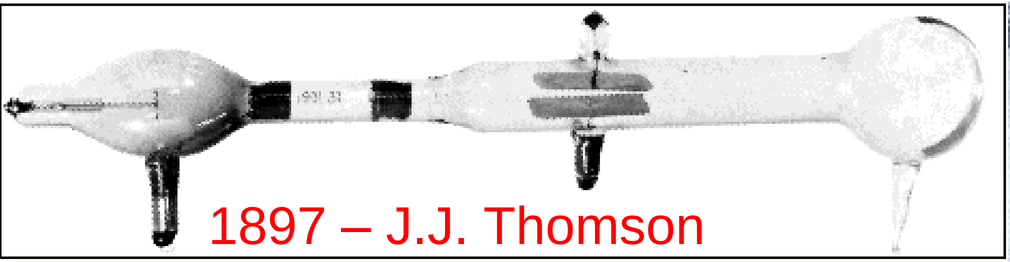
Cancer therapy

- Treatments
- Radiotherapy
- Charged particle therapy

Advantages of FFAGs for these applications

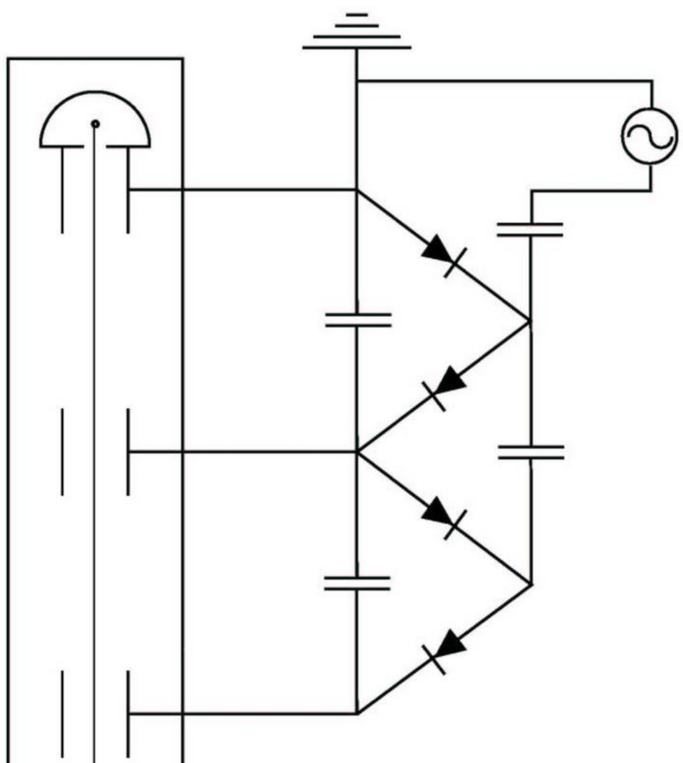
Particle Accelerators

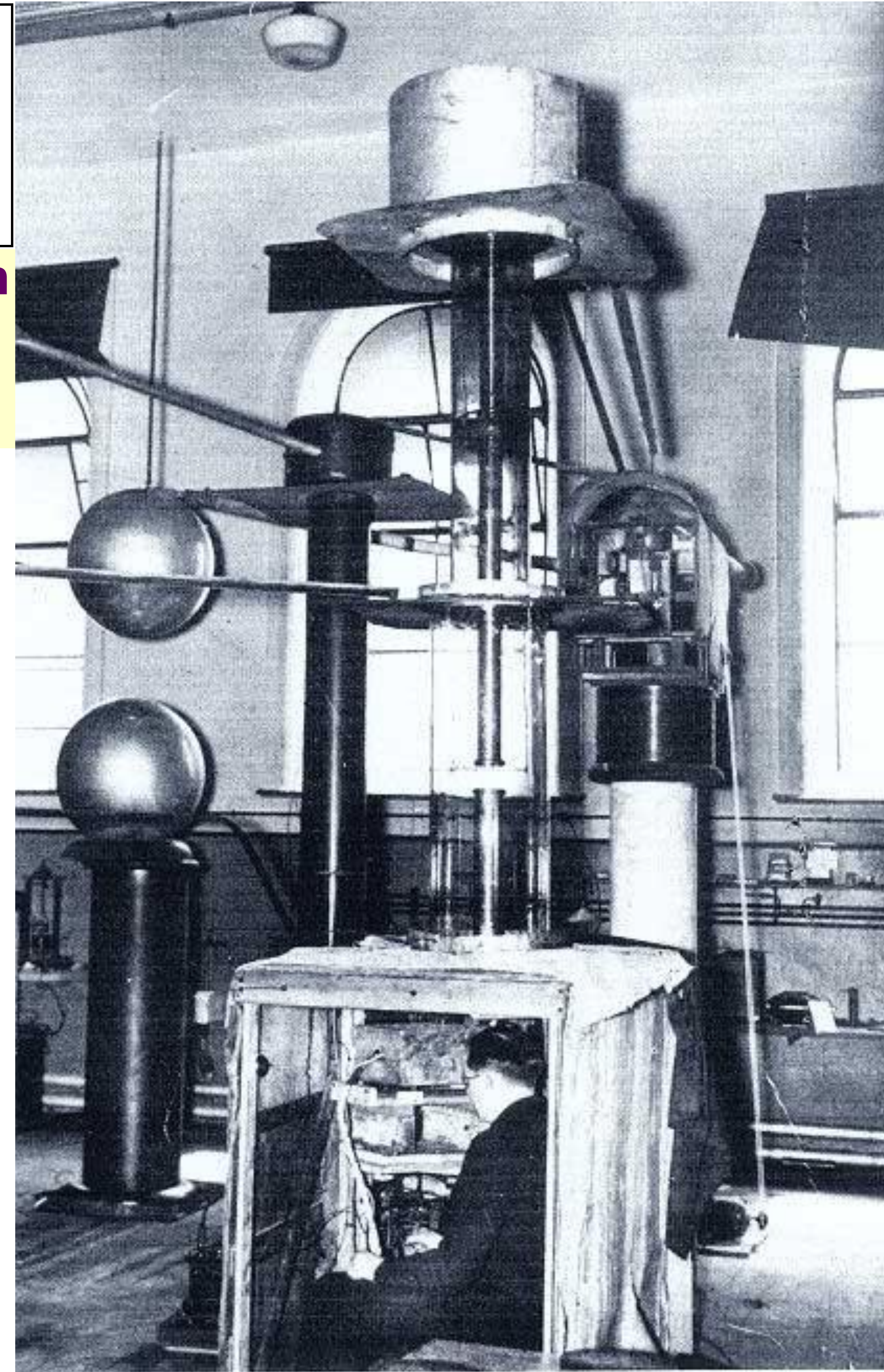
- Used to increase KE/momentum of charged particles
- All charged particles accelerated: e^-, p^+, H^-, $ions^{n+}$
- Acceleration via electric fields
- DC........electrostatic acceleration:
  - cathode ray tube
  - voltage multiplier
  - van der Graaff generator
  - etc
- Energy limited by electrical breakdown



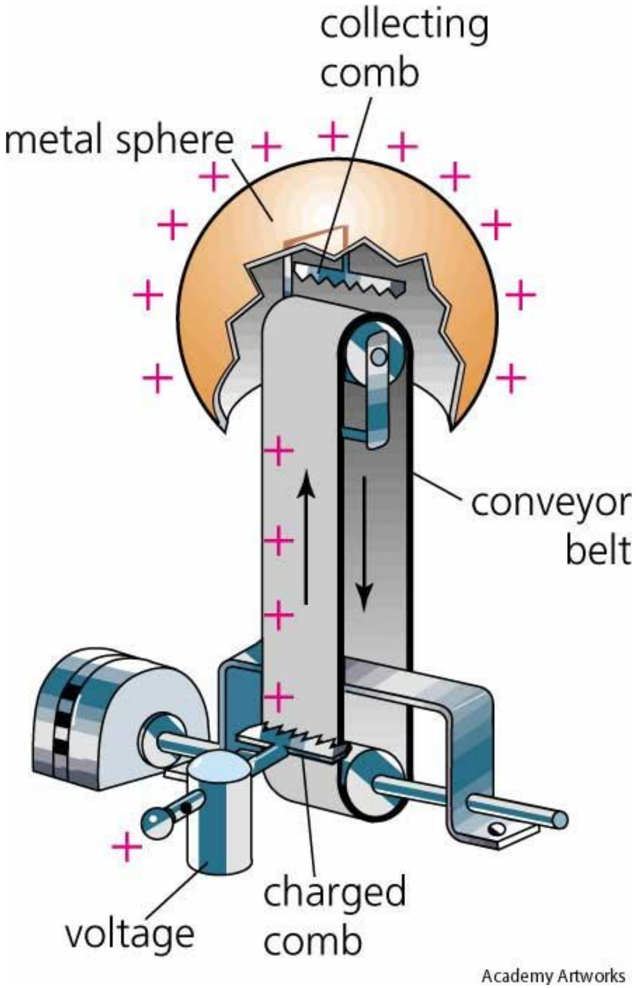
1897 – J.J. Thomson

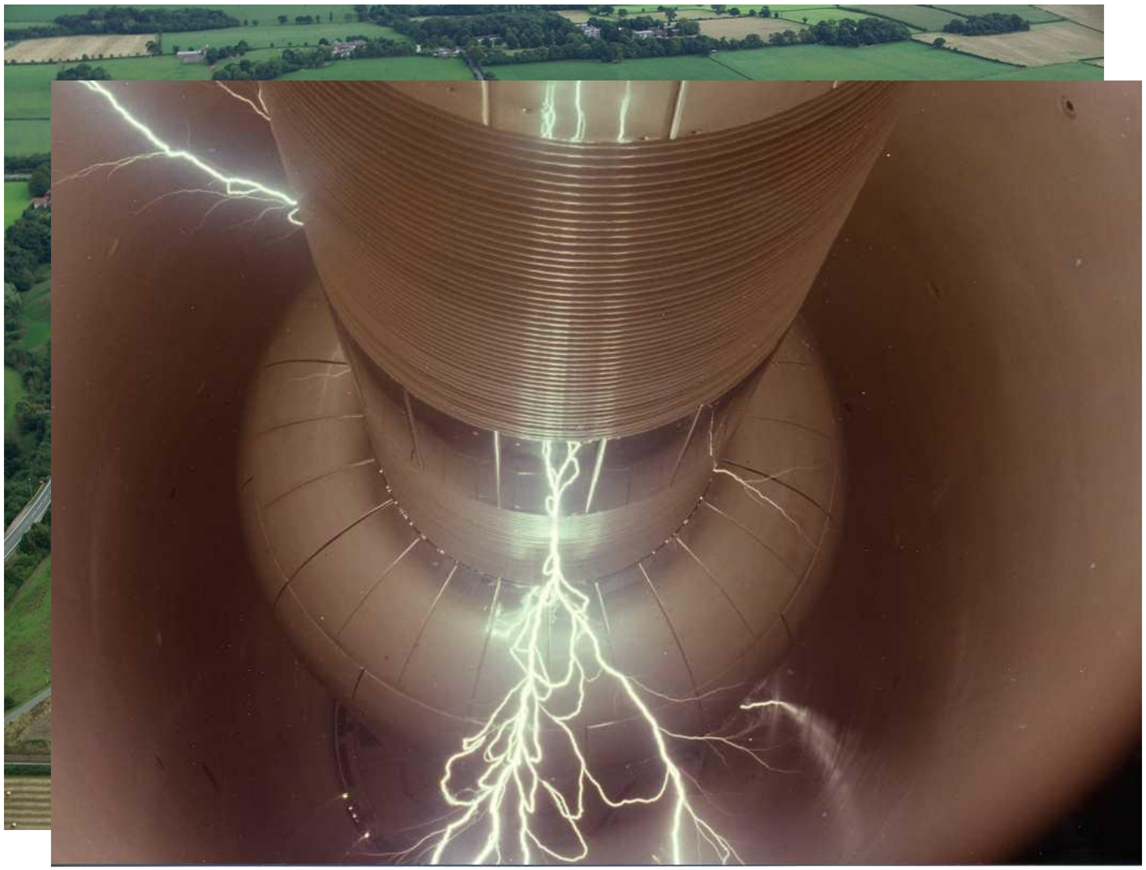
John Cockcroft & Ernest Walton
Voltage Multiplier
Cavendish Laboratory, 1932.





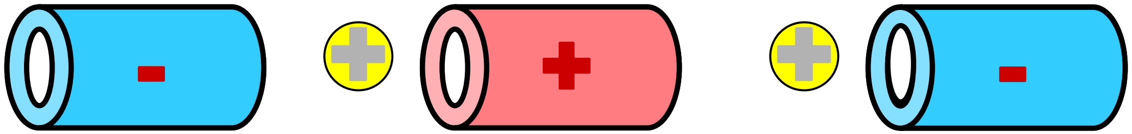
Particle Accelerators





Van der Graaff generator

Particle Accelerators



Alternating Radio Frequency voltage.
Each step gives a small energy increase to the particle.

Particle Accelerators

Linear accelerator.
Easier to design & operate.
But expensive at higher energies.

400 MeV p^+ linac at Fermilab

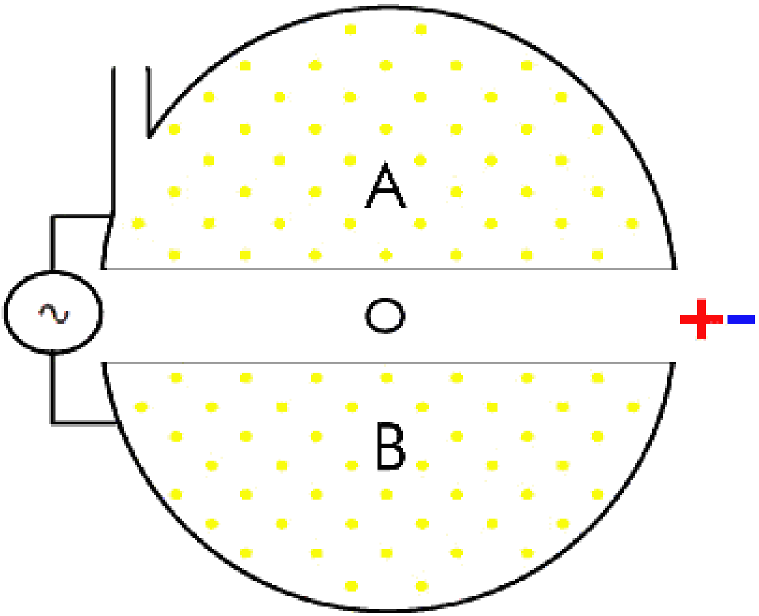
Particle Accelerators

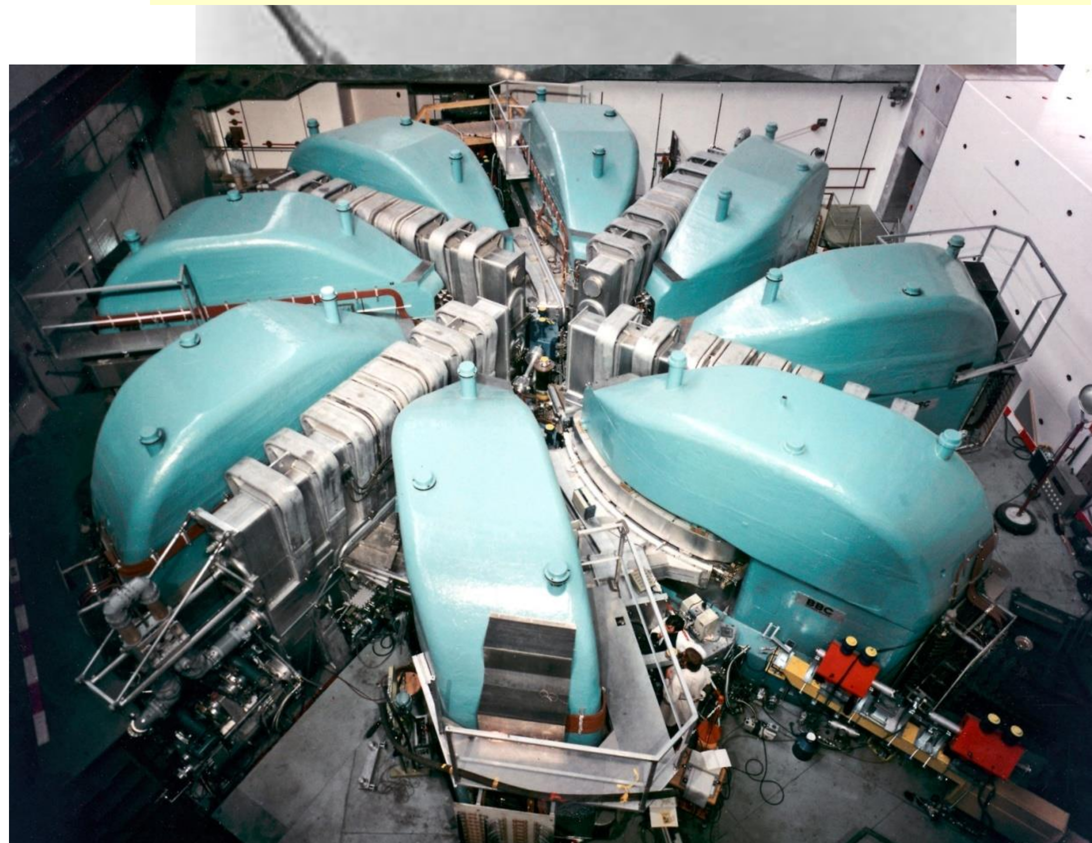
"Circular" accelerators:
1st type: cyclotrons

First circula... ...erator built by
Ernest O. La... ...y Livingston at
...0.

Energy : ... ...ter = 13cm

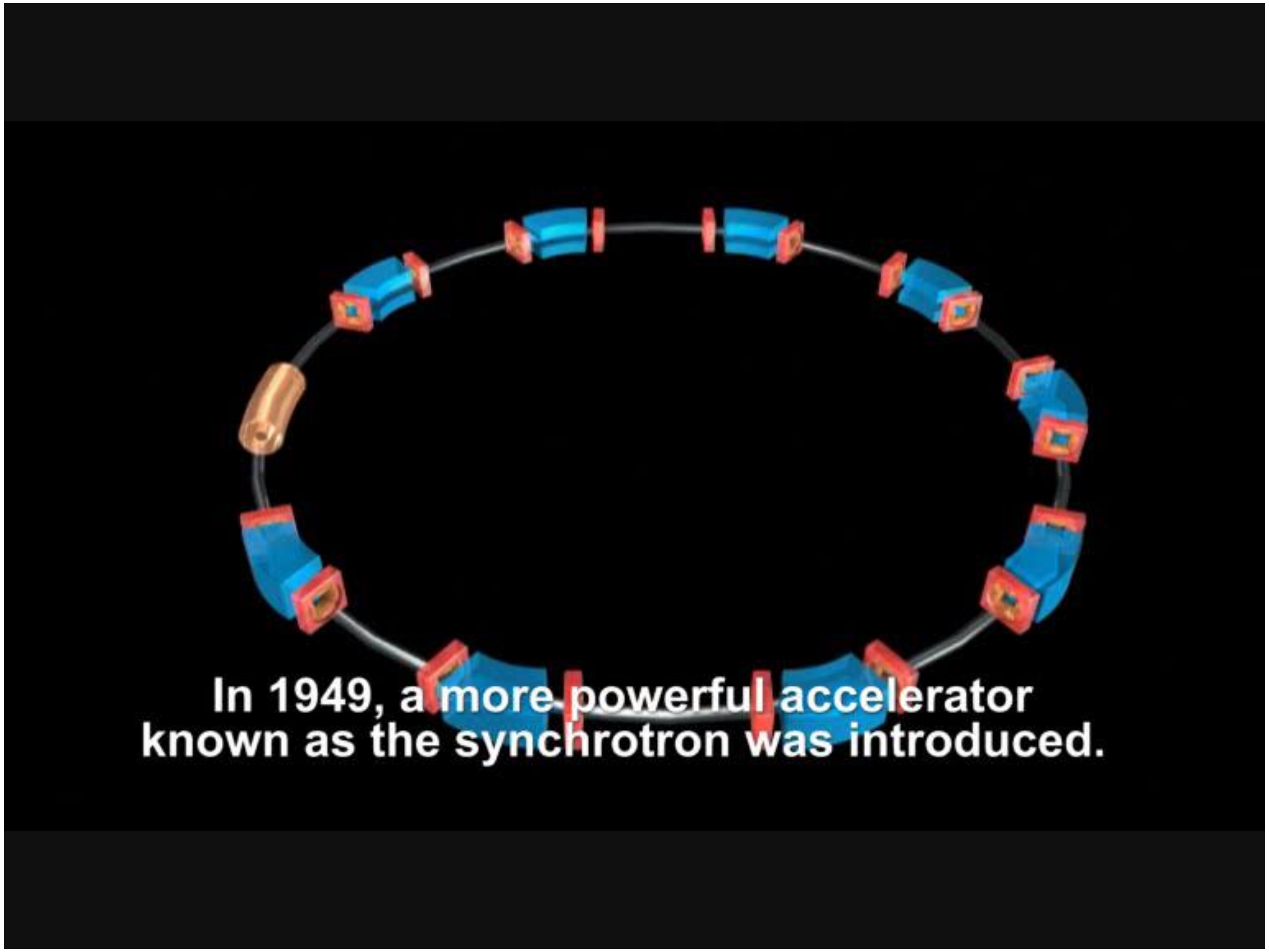
PSI cyclotron
600MeV



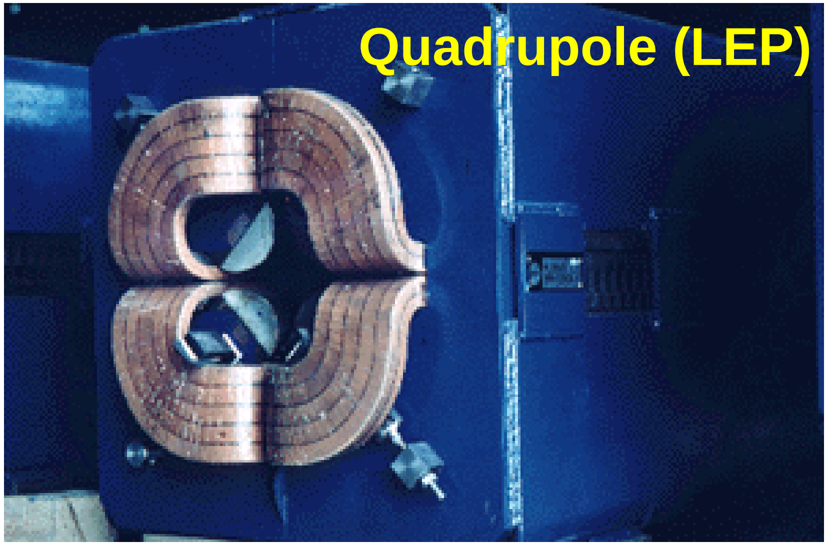


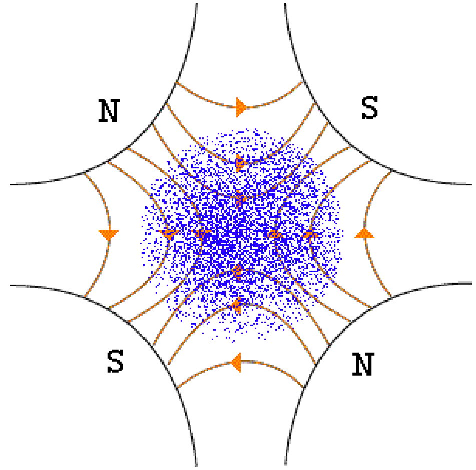
Particle Accelerators

"Circular" accelerators:
2nd type: synchrotrons



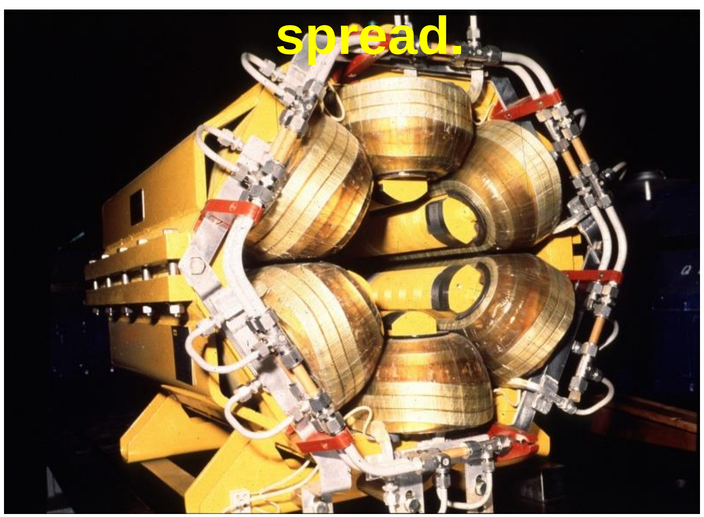
Particle Accelerators

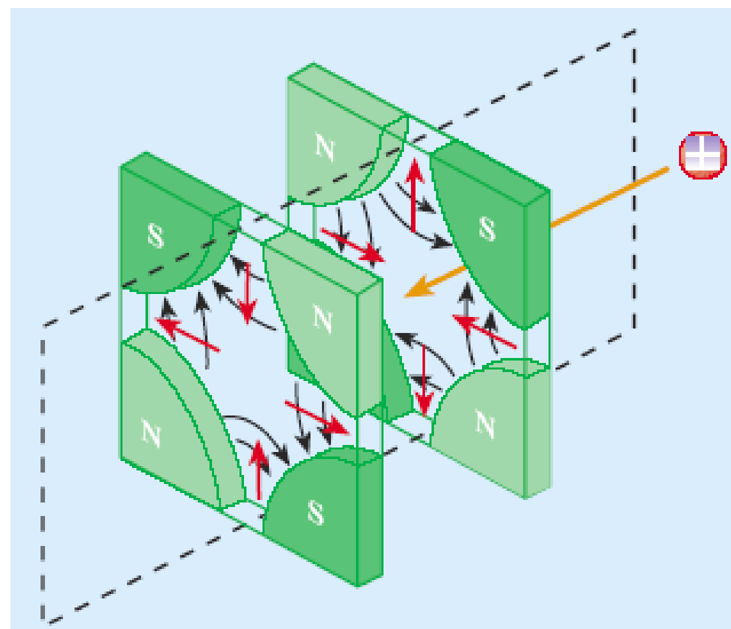




Alternating Gradient or Strong Focussing Beam alternately focussed in horiz and vert planes.

Sextupole (LEP) Correction of chromatic spread.





RAL 1957 2007
Celebrating 50 years of world class science

Particle Accelerators

Particle Accelerators

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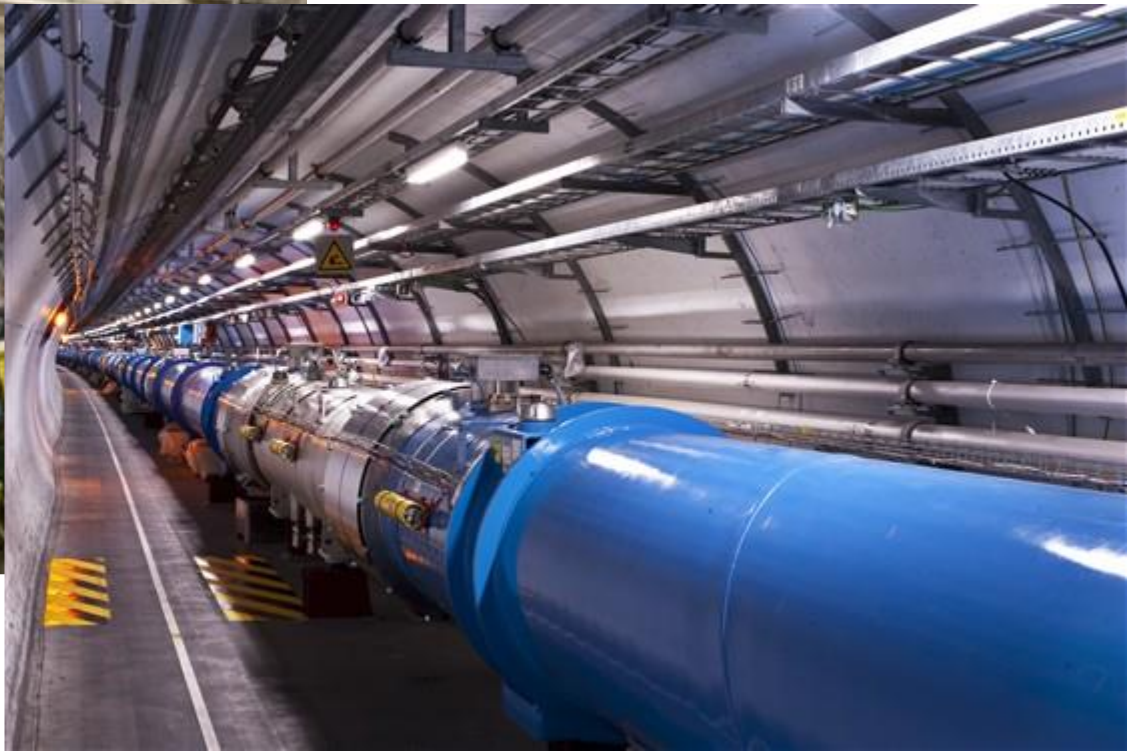

Accelerator Applications

- **Accelerators created for Particle Physics**
- **Many developments driven by PP**
- Now used for other applications
  - >30000 accelerators already in use around the World
  - Annual sales: >$3.5B
  - Annual product, etc, sales: >$0.5T
  - Fit into a few broad categories:
    - Energy
    - Environment
    - Healthcare
    - Industry
    - Security and defence
    - Research

Applications

Treating cancer

Making better semi-conductors

>30000 accelerators in use world-wide:

- 44% for radiotherapy
- 41% for ion implantation
- 9% for industrial applications
- 4% low energy research
- 1% medical isotope production
- <1% research

Applications

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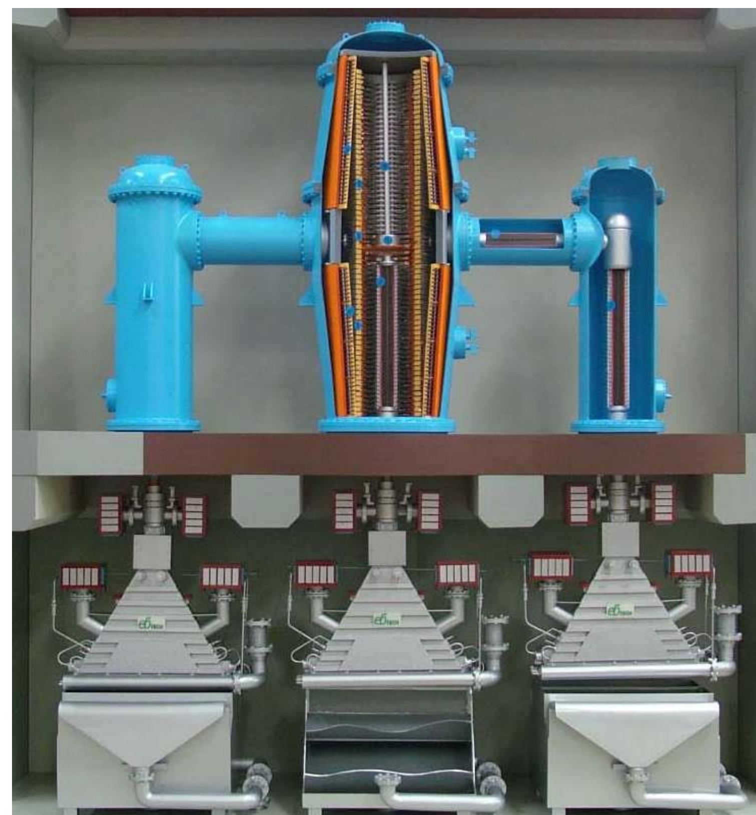
"Curing" materials;
sterilisation;
carbon dating;
treating flue gases;
treating water;
etc



Applications

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- 44% for radiotherapy
- 41% for ion implantation
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- 4% low energy research
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Microanalysis of materials, mass spectroscopy, PIXE, etc

Applications

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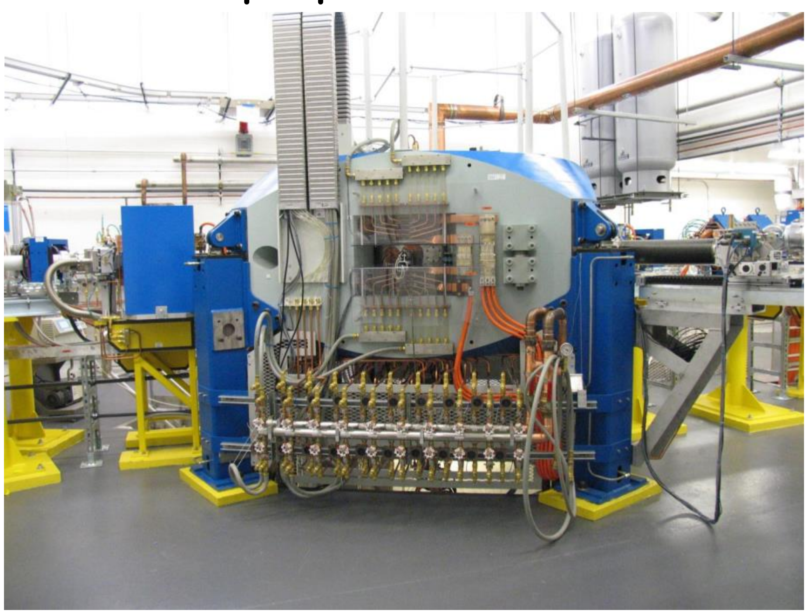
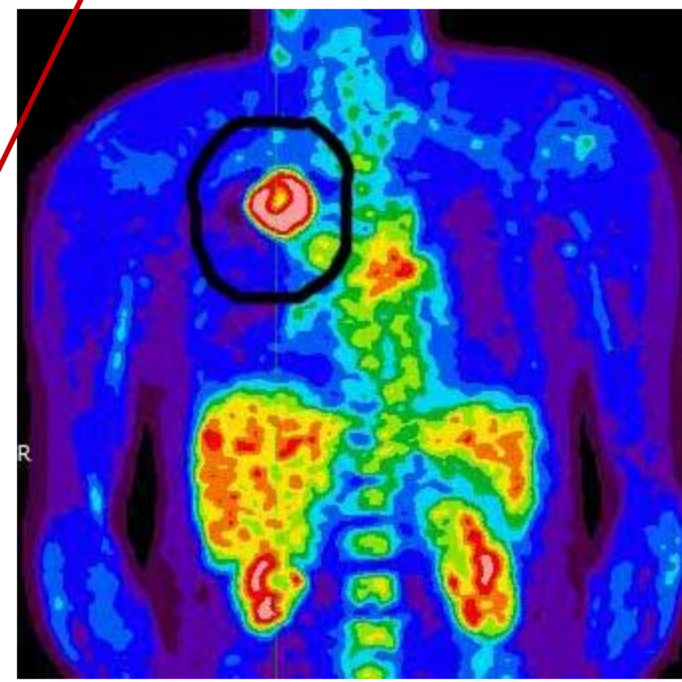
For PET and SPECT medical imaging, etc





Applications

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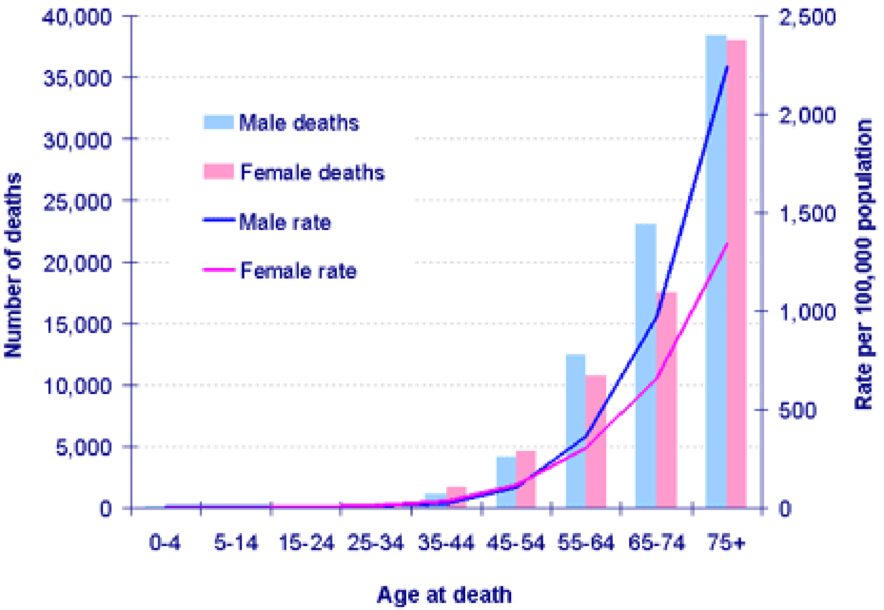
- <1% research

Physicists Introduction to Cancer

It starts with mutations of a single cell
typically 6 are required to make it cancerous

- Mutations accumulate over time
- Can occur by accident
- Usually requires a "carcinogen"
  tobacco (50)
  other chemicals
  radiation (e.g. sun)

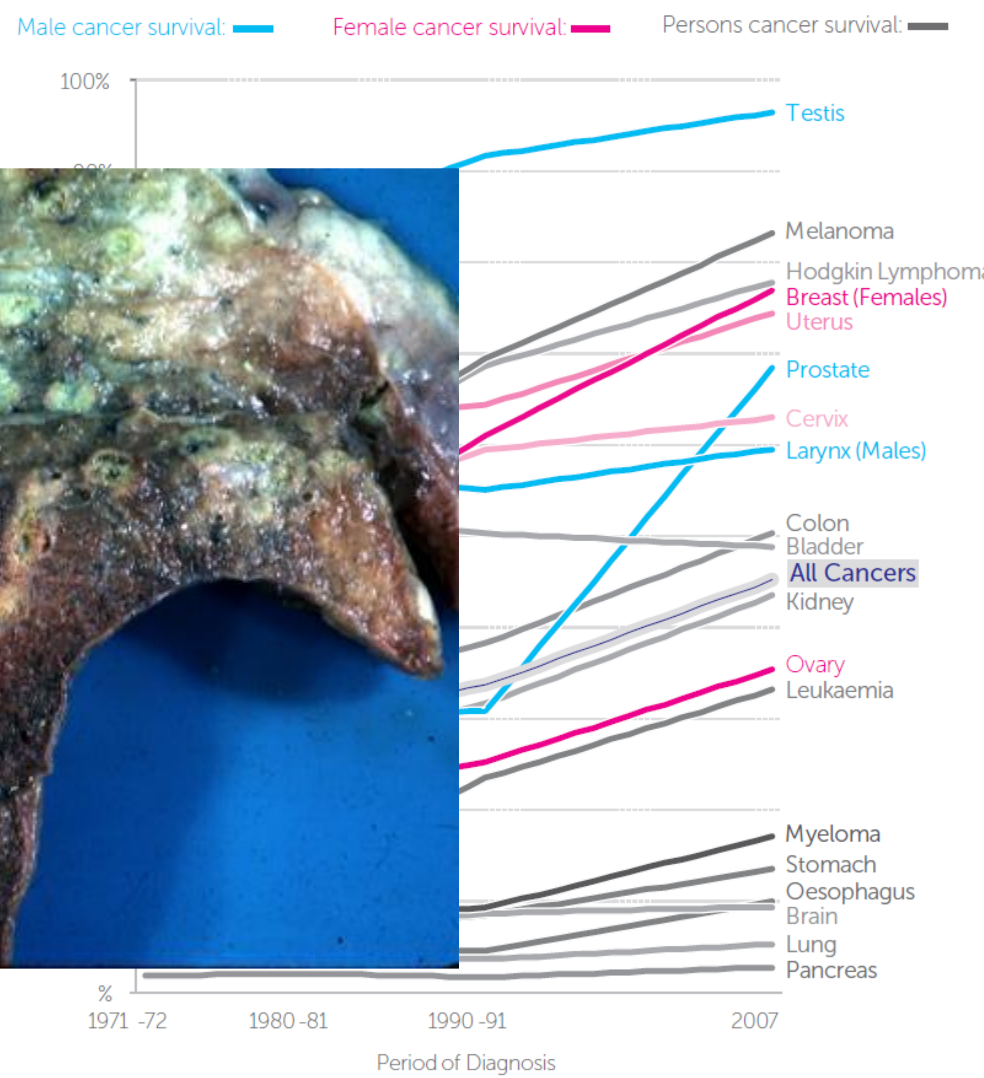
Figure 2.1: Number of deaths and mortality rate, all malignant neoplasms, by age and sex, UK, 2004



Some Statistics

Survival Trends for Selected Cancers: 1971-2007

Ten Year Relative Survival (%), Adults (15-99 Years), Selected Cancers, England and Wales



Treatments

- Cancer therapy:

  It's all about minimising collateral damage!

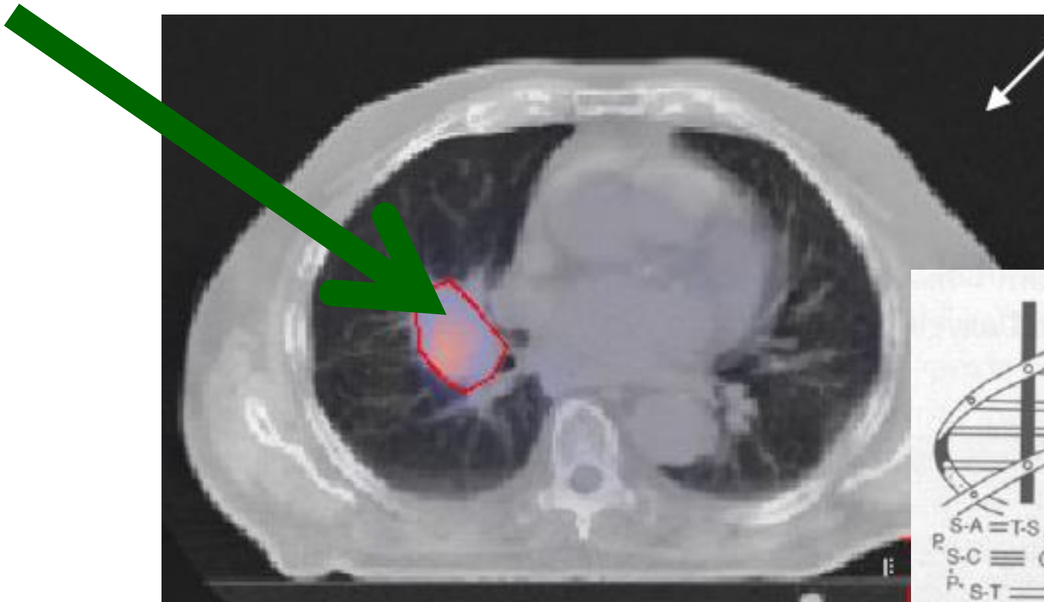
- Killing or removing just cancerous cells
- Damage to healthy cells leads to side-effects

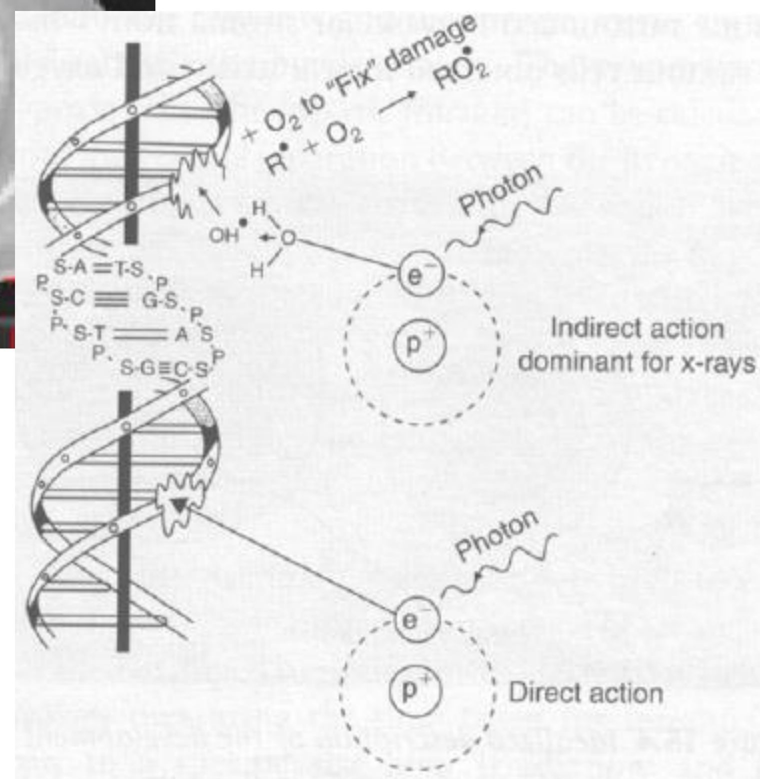
Three main types:

surgery
radiotherapy
chemotherapy

- Uses beams of ionising radiation
- Mainly X-rays, but see later
- Usually produced externally and directed onto tumour

Radiotherapy



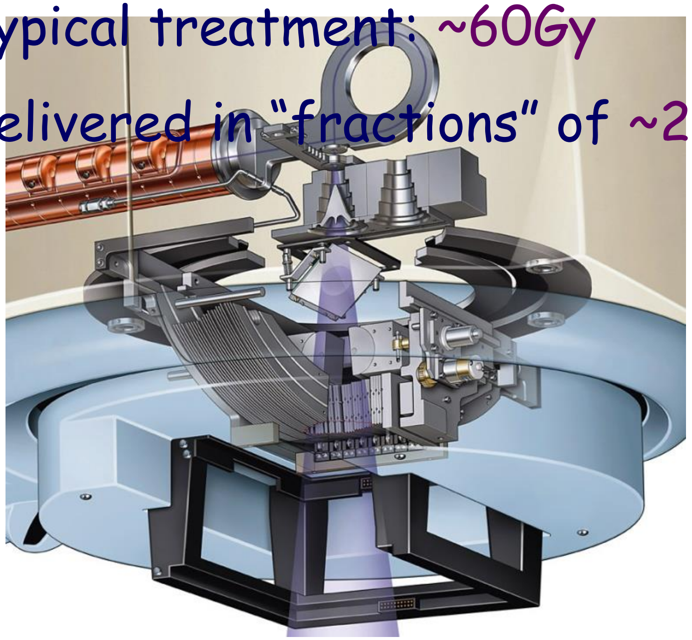


Ionisation from radiation kills cells in two ways

Multiple DNA chain breaks preferred

Radiotherapy

- "Standard" radiotherapy uses X-rays
- Created using electron linear accelerator
- Energy ~4-20 MeV
- X-rays produced in metal foil
- Typical treatment: ~60Gy
- Delivered in "fractions" of ~2Gy



Beam Delivery

- Old technique: treat whole tumour in one go

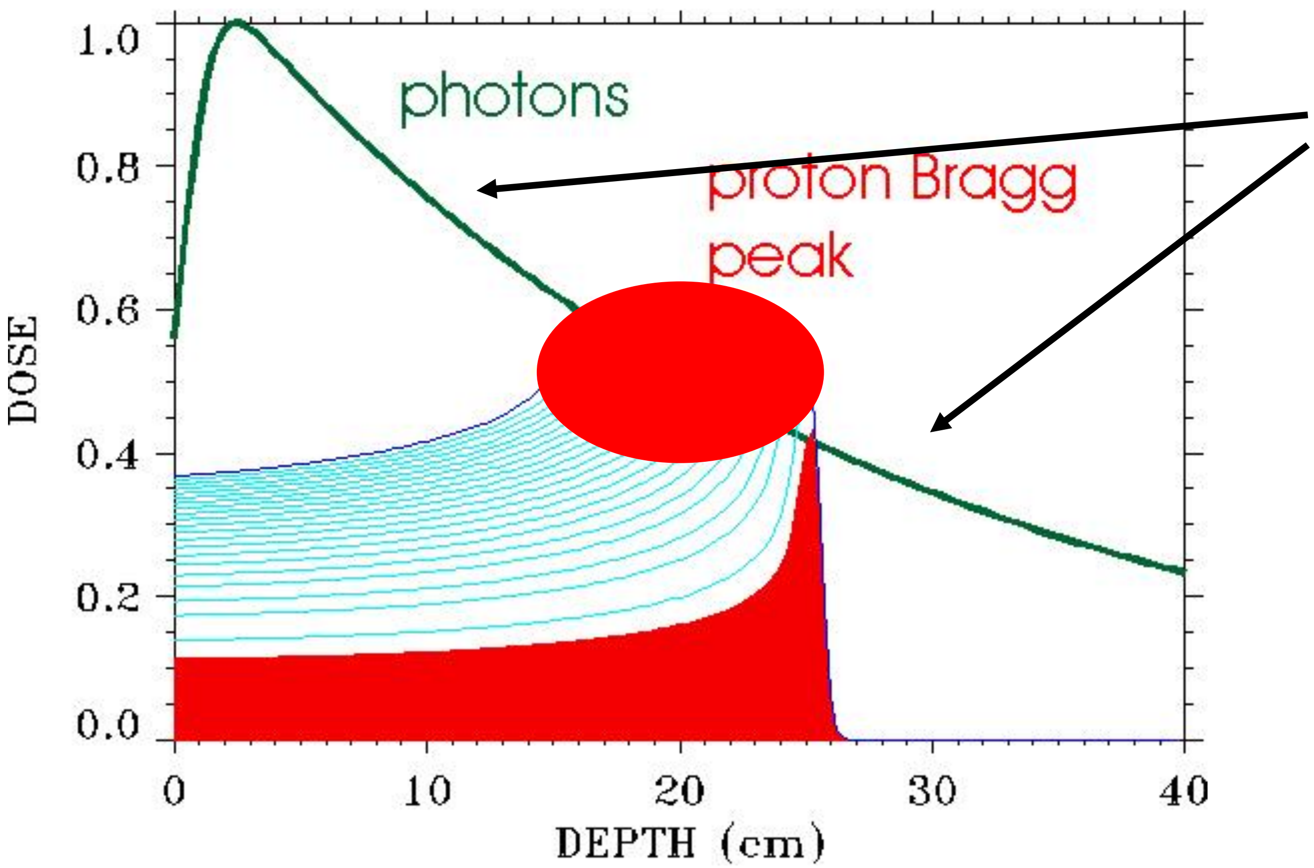
- Newer technique: Intensity Modulated Radiotherapy

Dose Localisation

Varian: IGRT

CyberKnife

Dose Localisation



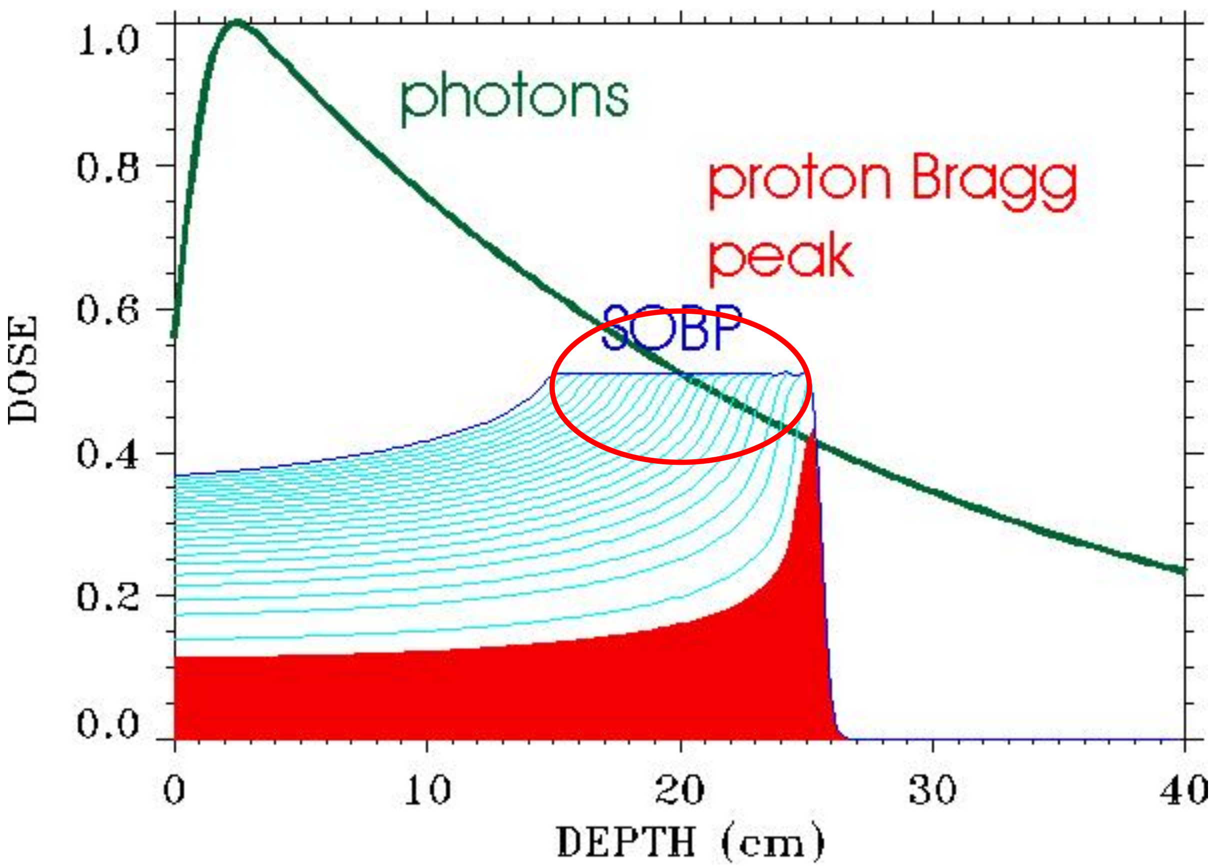
Damage to healthy tissue: side-effects!

But……… healthy cells have more repair mechanisms…

Fractions and IMRT

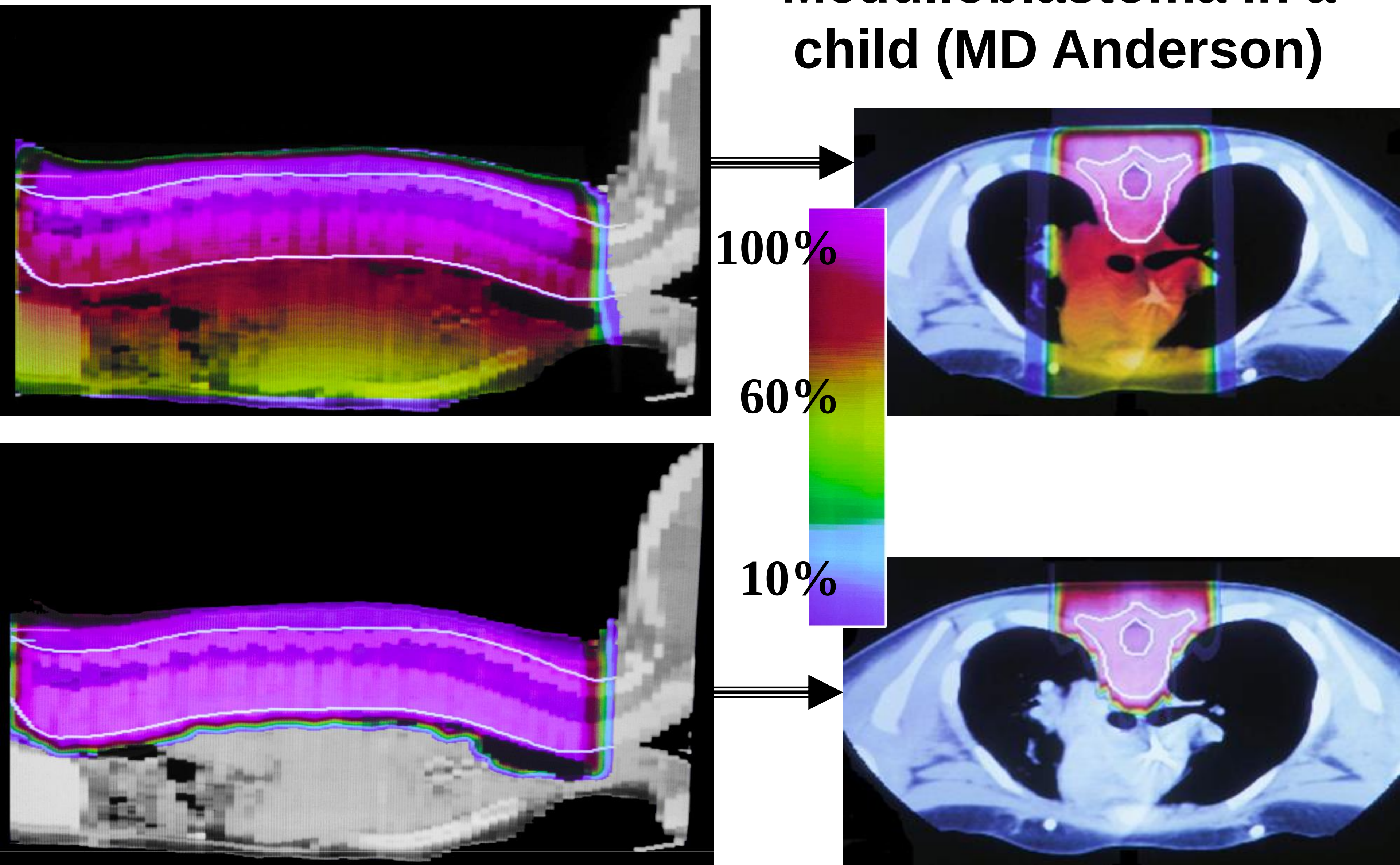
It's possible to do better!

Dose Localisation

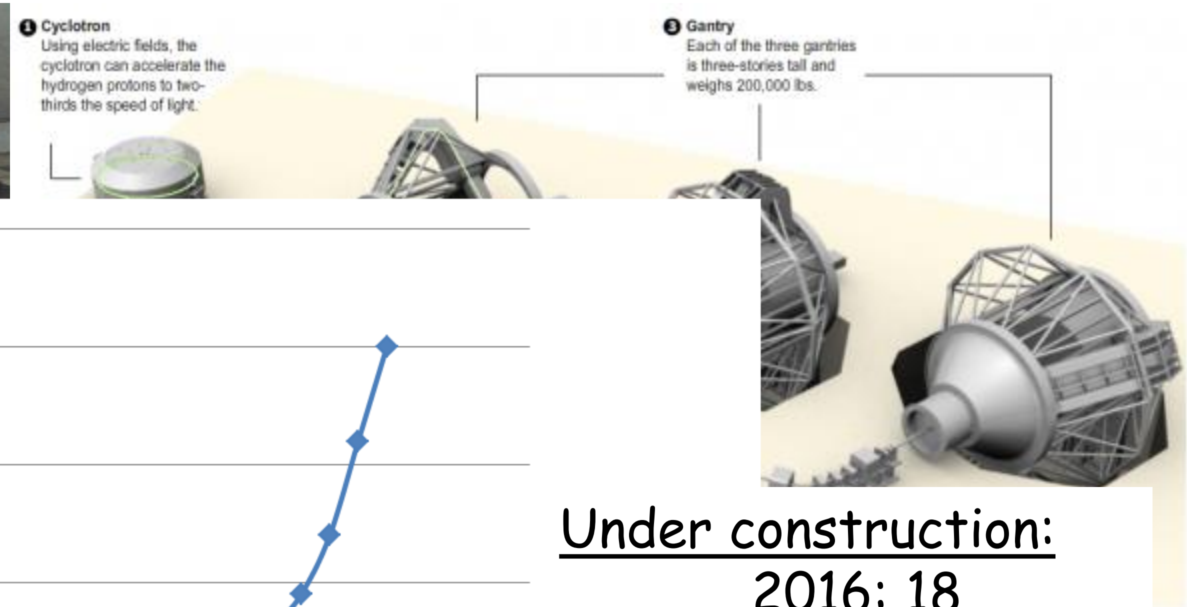


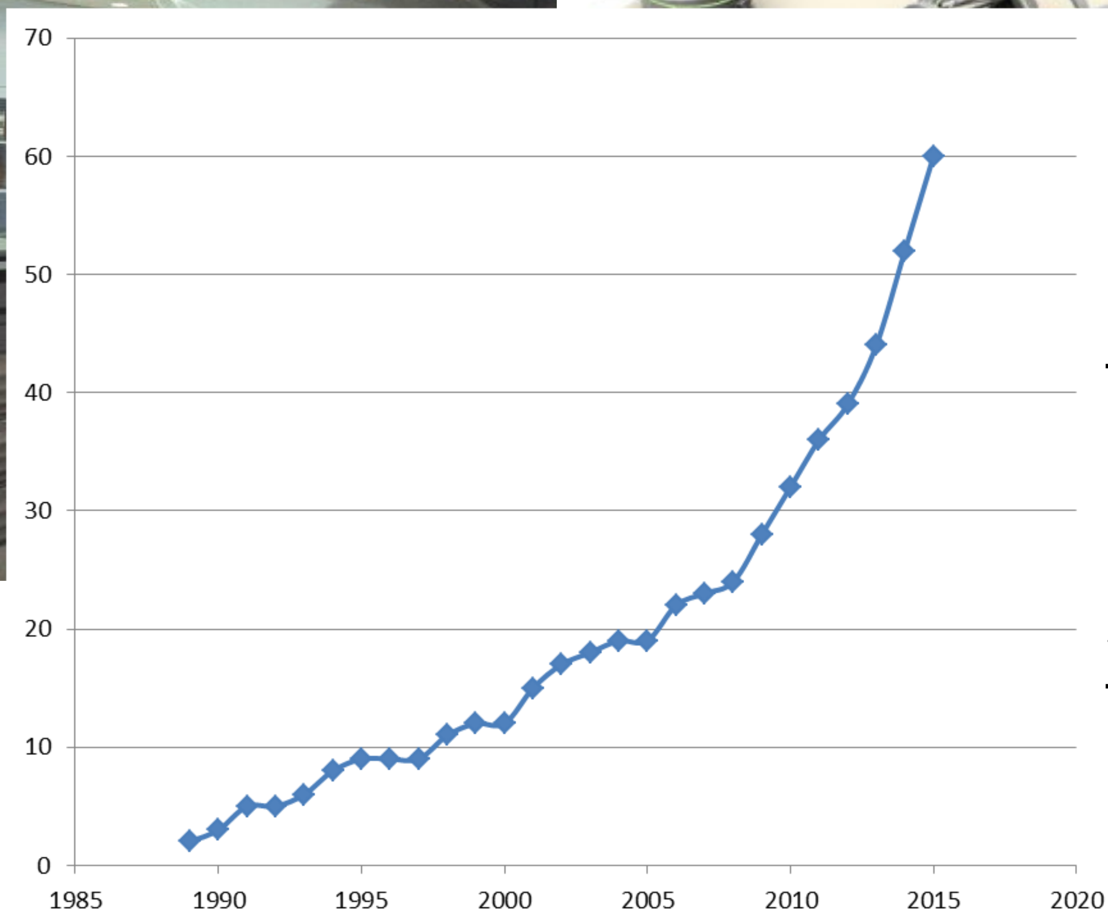
Dose Localisation

Medulloblastoma in a child (MD Anderson)



Proton Therapy





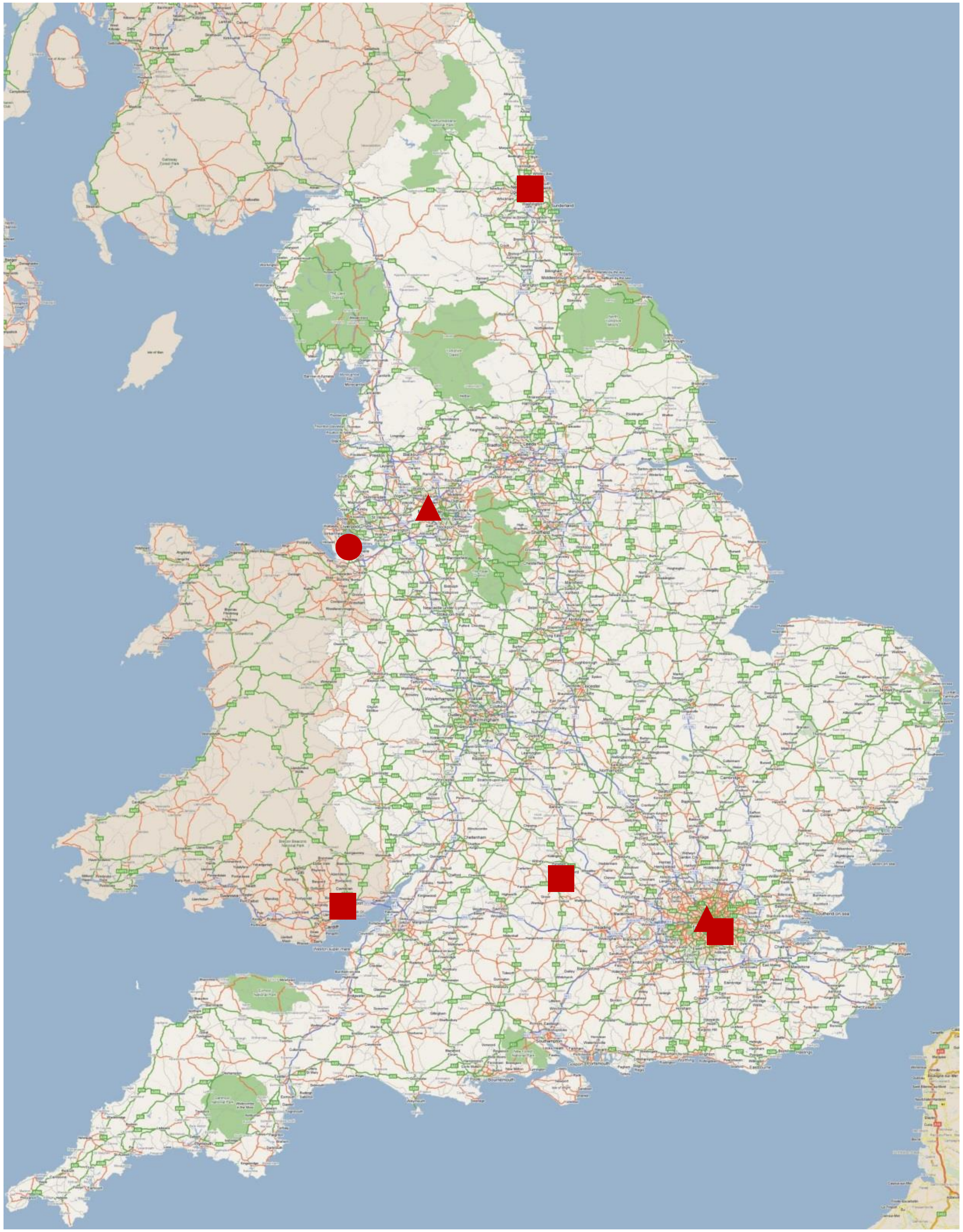
Under construction:

2016: 18
2017: 6
2018: 6

In planning:

16

Proton Therapy



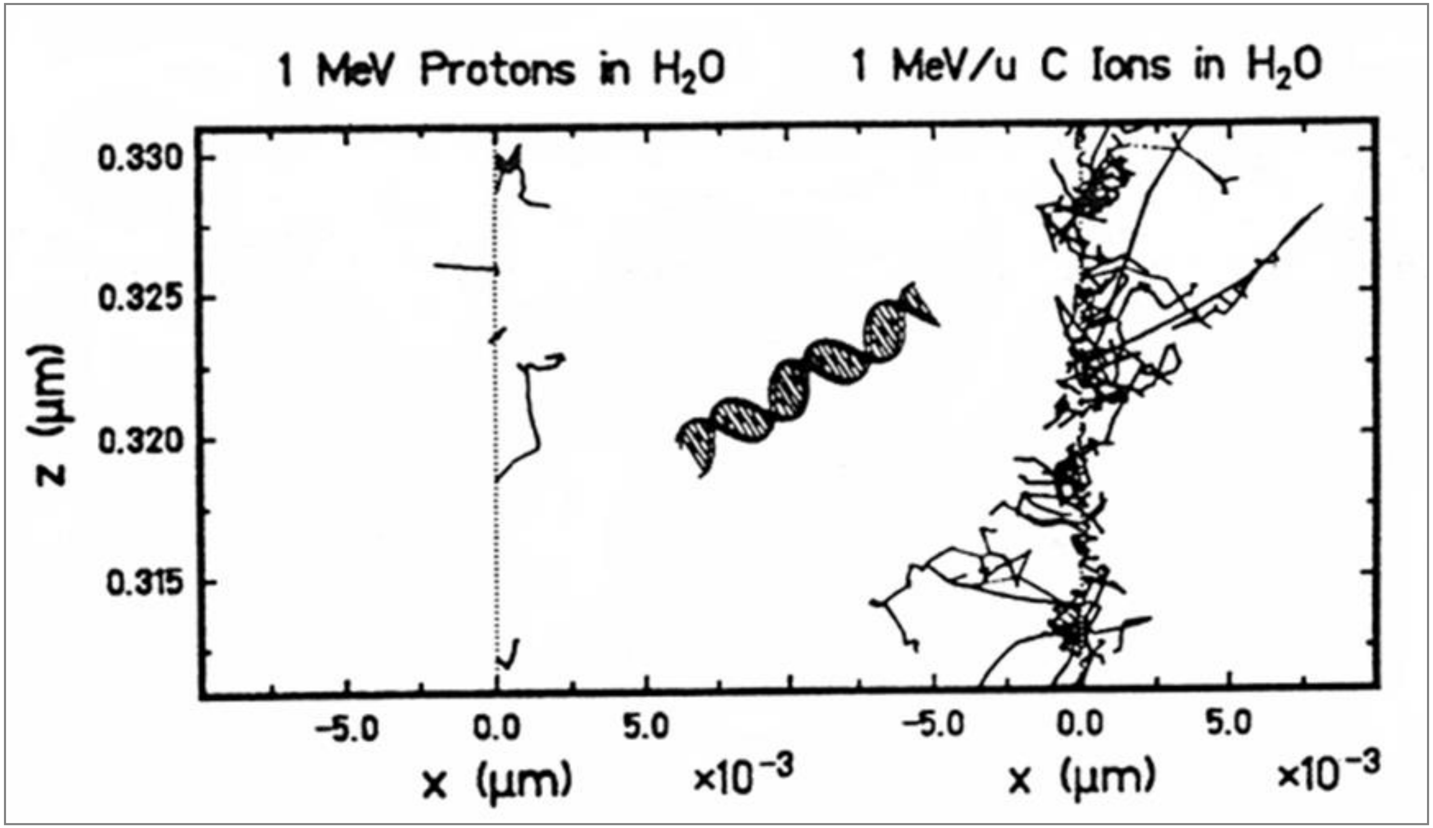
Proton Therapy

protonGuys.com

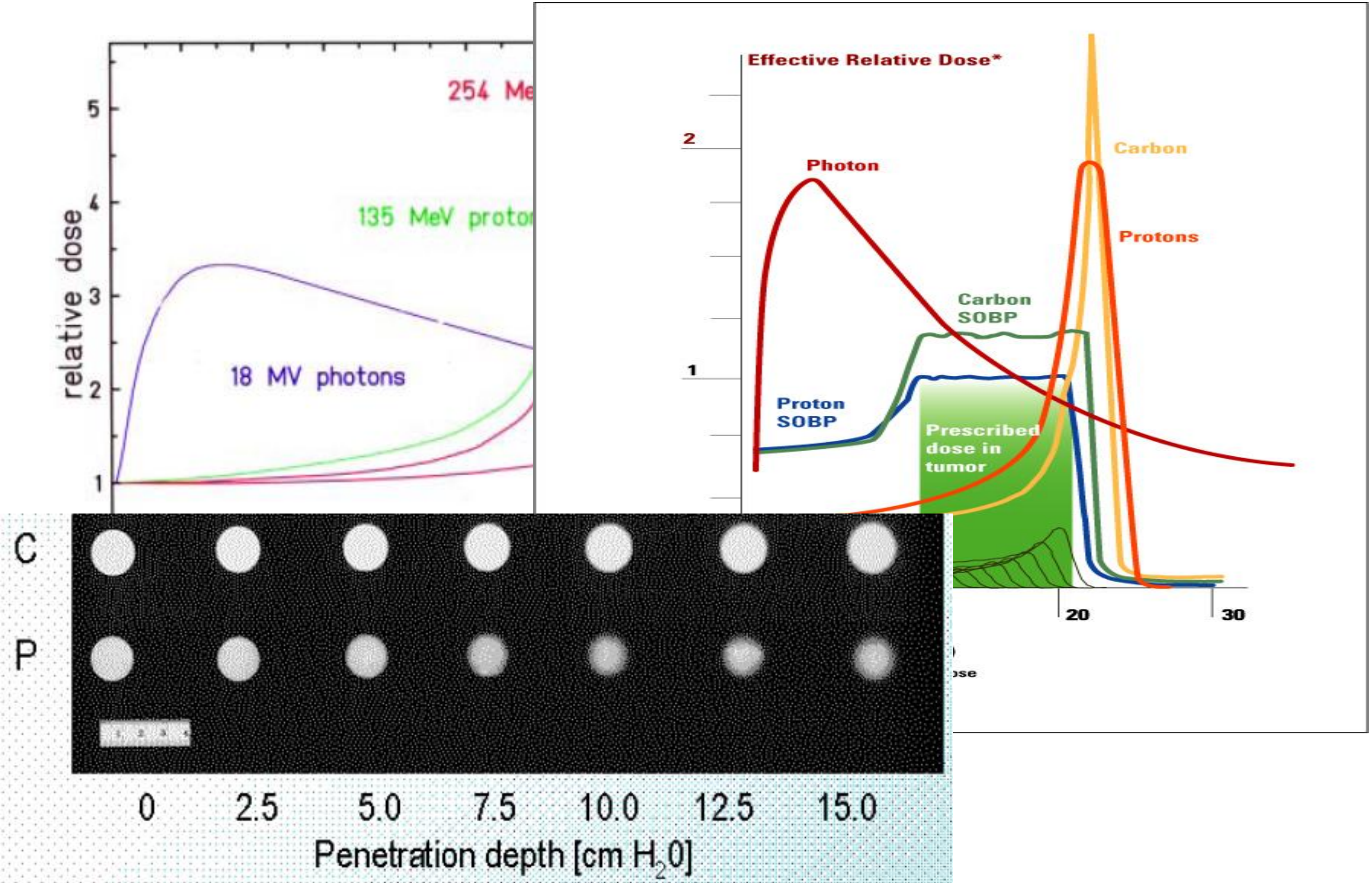
Other Ions

Group→ ↓Period	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

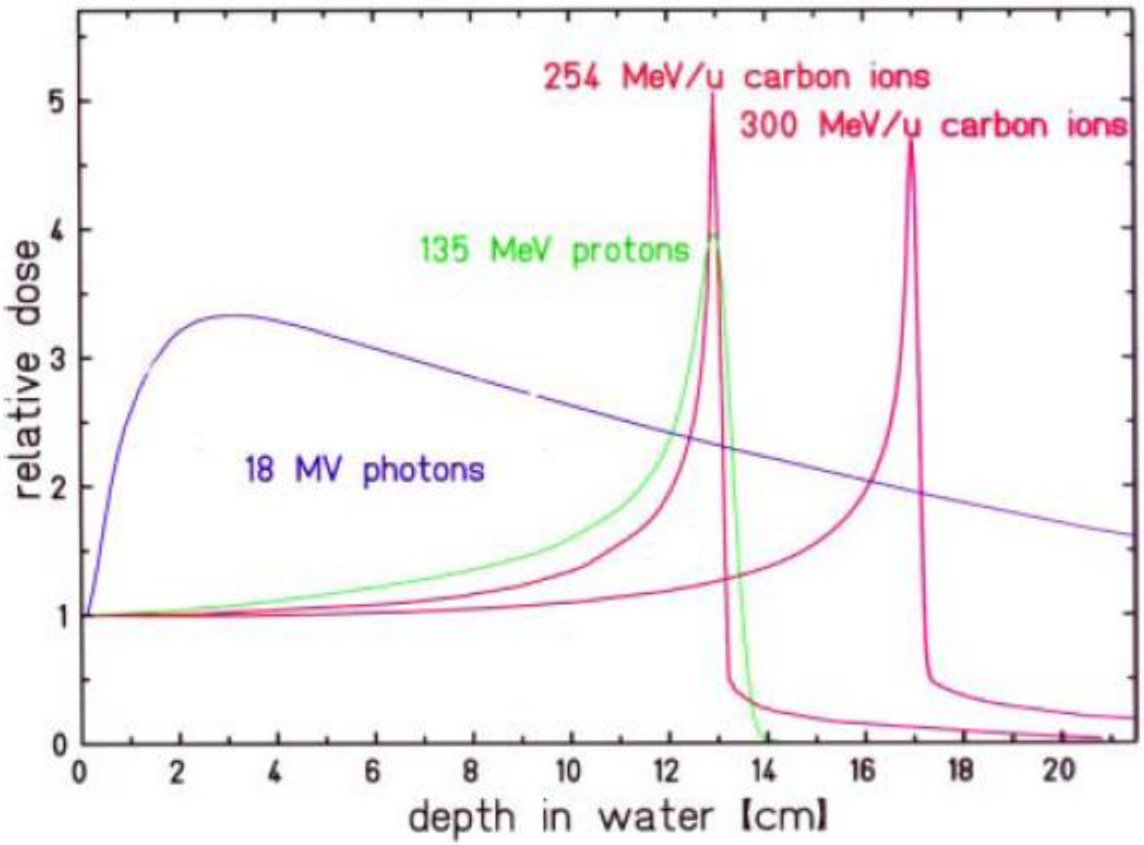
Dose Localisation



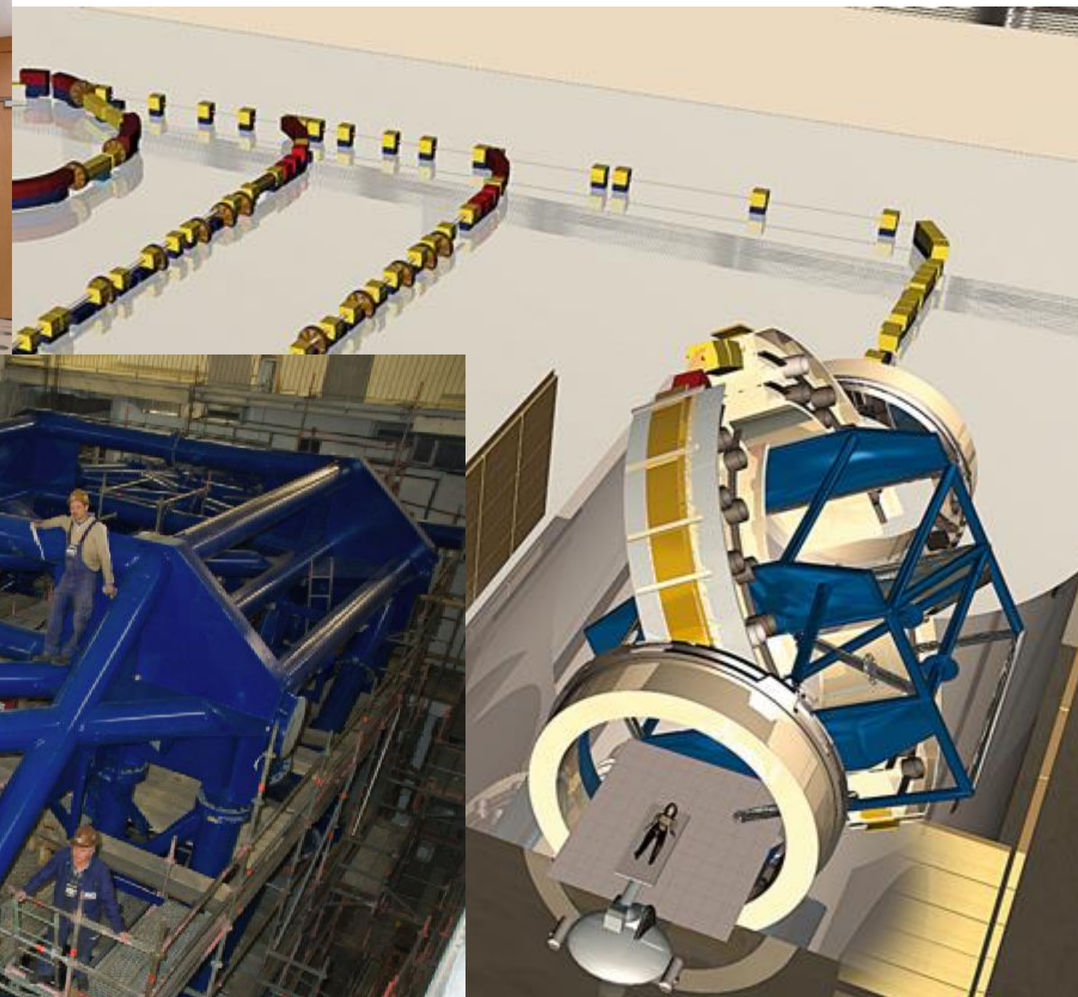
Dose Localisation



Dose Localisation



Charged Particle Therapy



Carbon Therapy

- In operation:
  - Europe: 3
  - China: 2
  - Japan: 5
- Construction:
  - Europe: 1
  - China: 1
  - South Korea: 1
- Significant PP input to those in Europe
- Two based on CERN design
- Main problem: size!

Roles of FFAGs

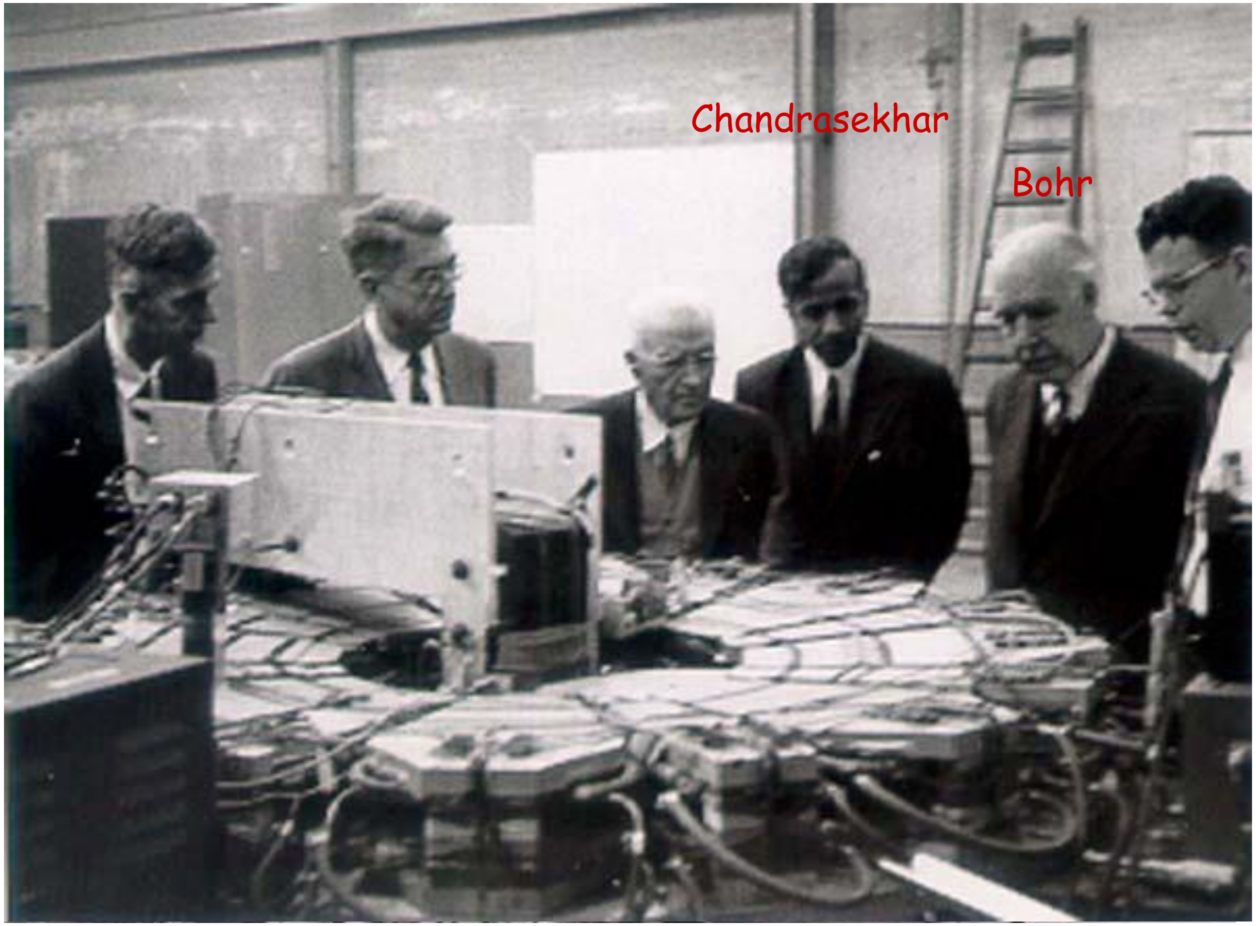
Fixed Field Alternating Gradient accelerator

Cyclotron-like (Fixed Field) — **Synchrotron-like** (Alternating Gradient)

- Combines features of cyclotrons and synchrotrons
- Interesting for particle therapy, ADSR, PP and others
- Particularly in intermediate energy range

A Brief History of FFAGs

- 1950s/60s: most extensive work at MURA



20 to 400 keV machine

Operated at MURA in 1956

A Brief History of FFAGs

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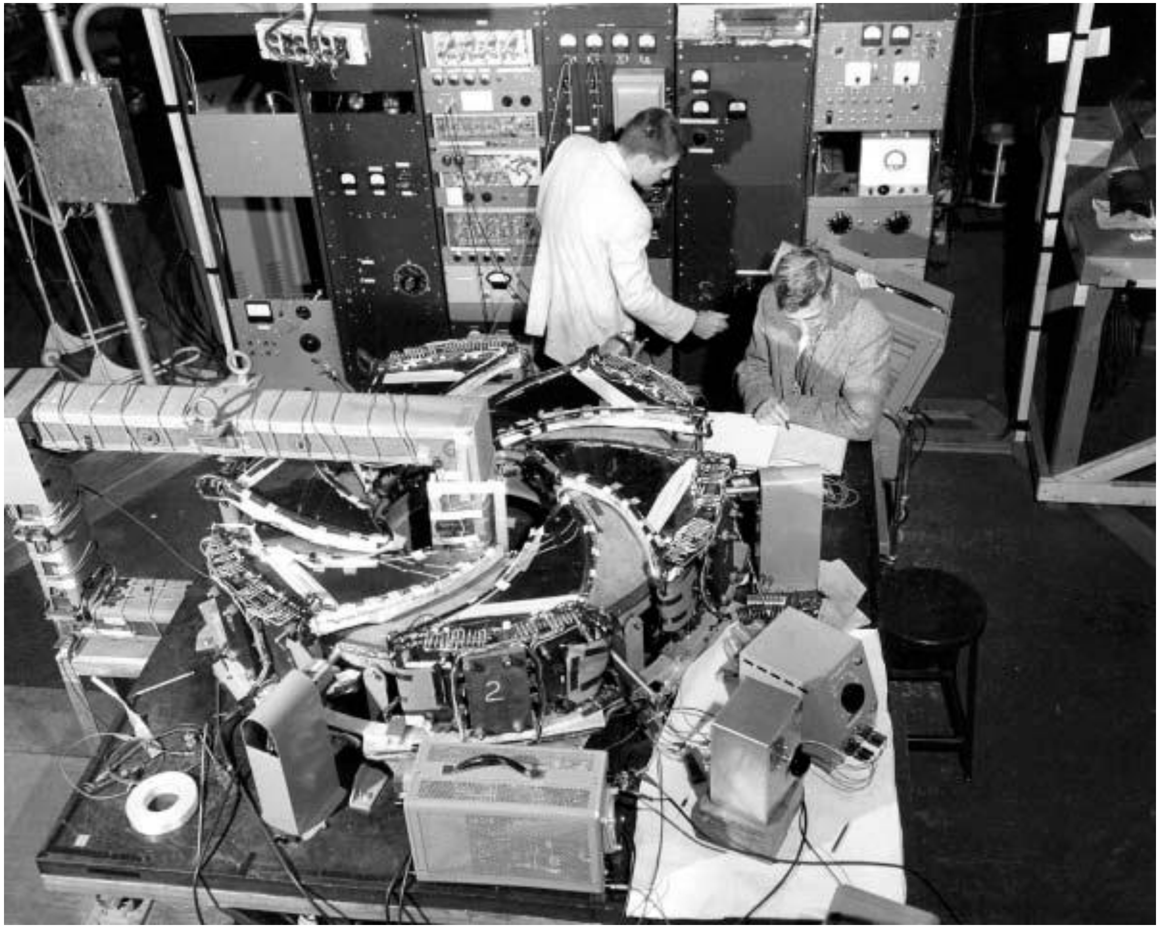

Spiral sector machine

Operated at MURA in 1957

A Brief History of FFAGs

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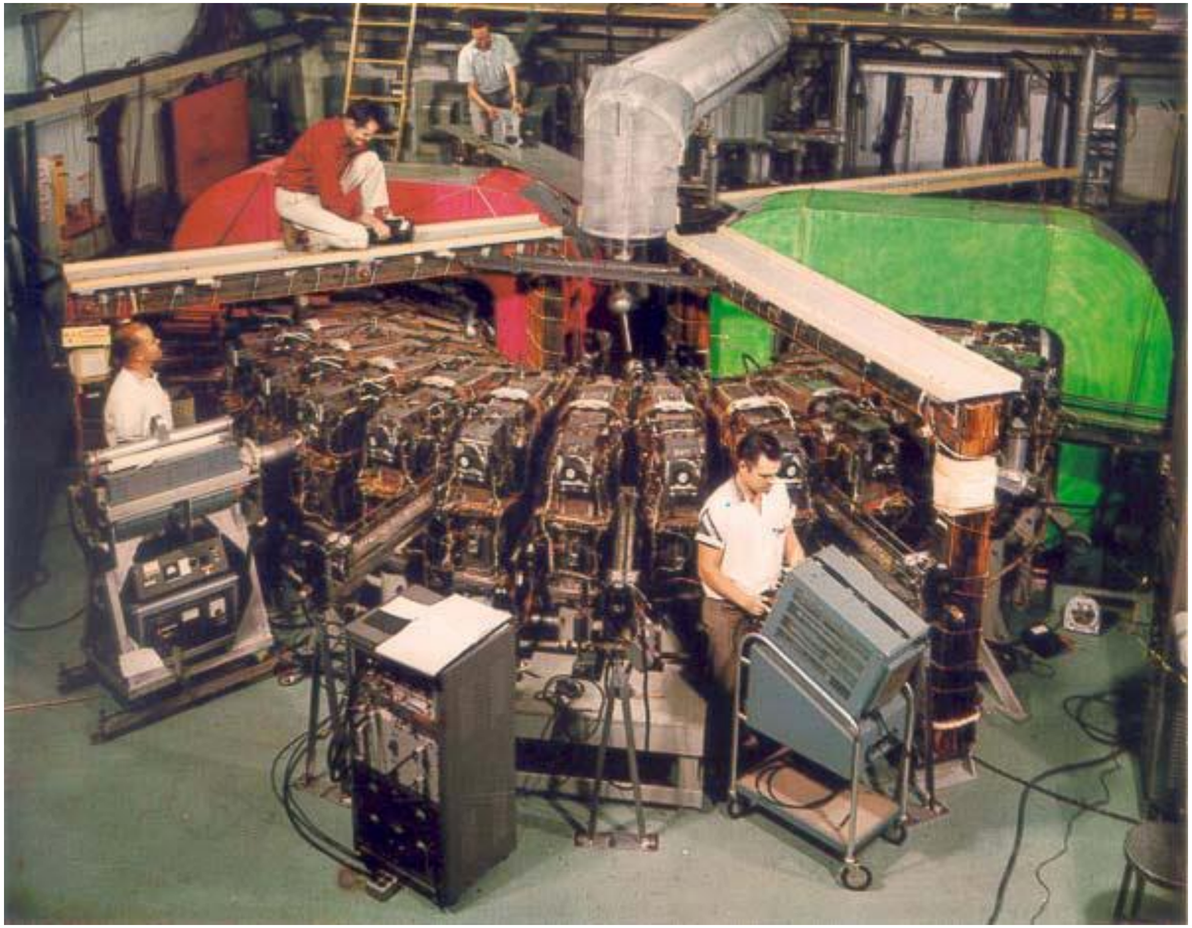


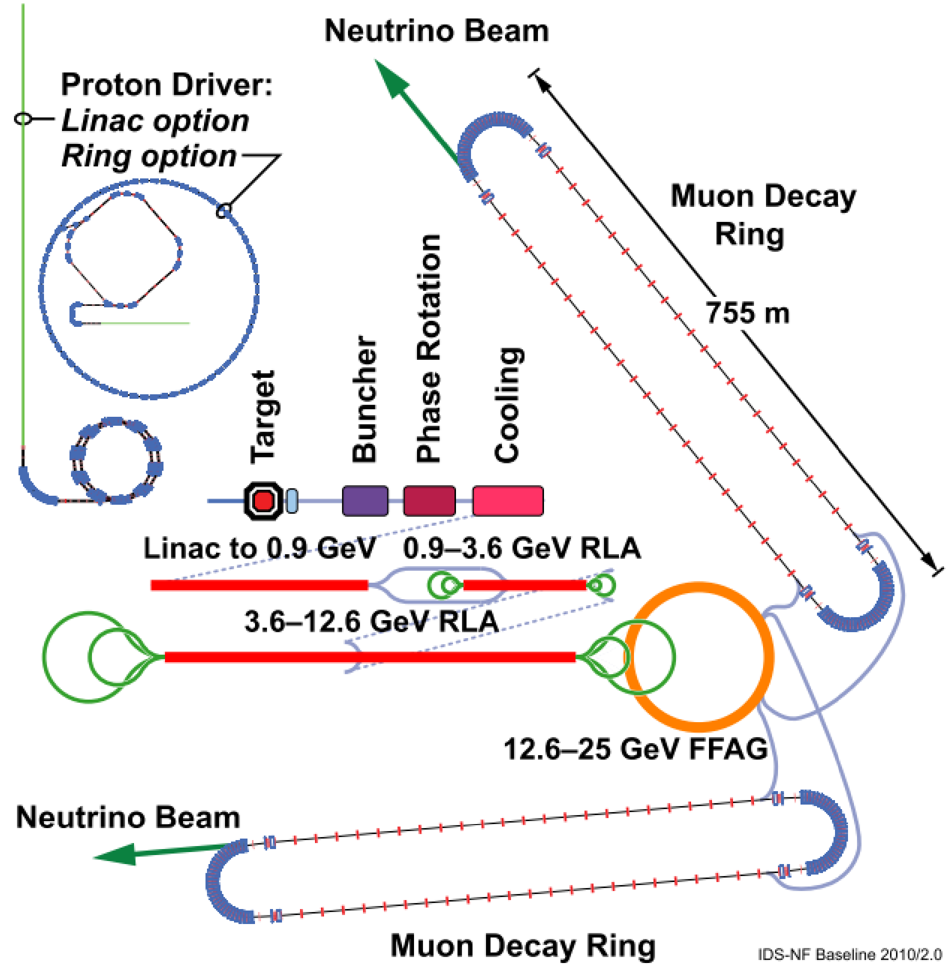
100keV to 50MeV machine

Operated at MURA in 1961

A Brief History of FFAGs

(Non-scaling) FFAG Development

- Originally invented for:
  - fast acceleration
  - large DA
- 2004:
  - studies for applications
  - unique features
  - needed to build one

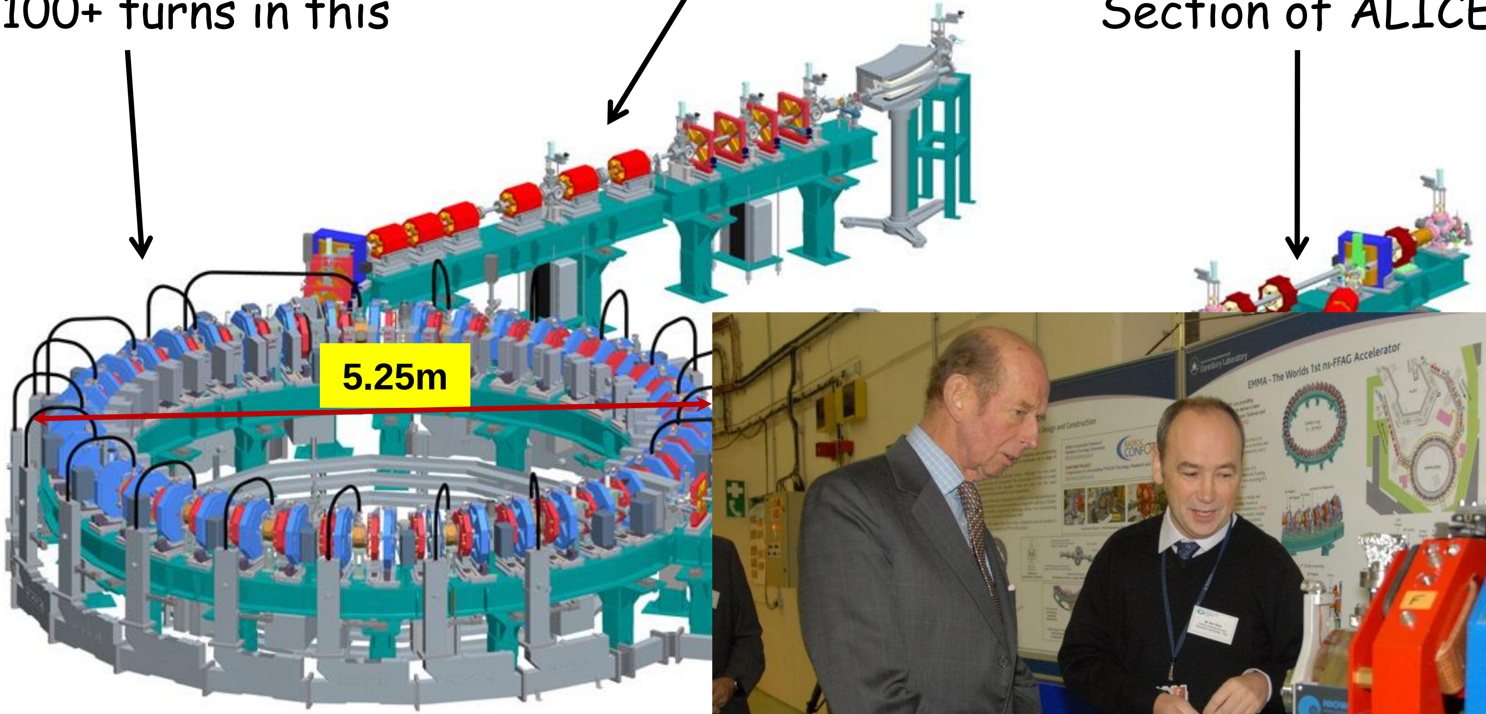


EMMA

Diagnostics beam line

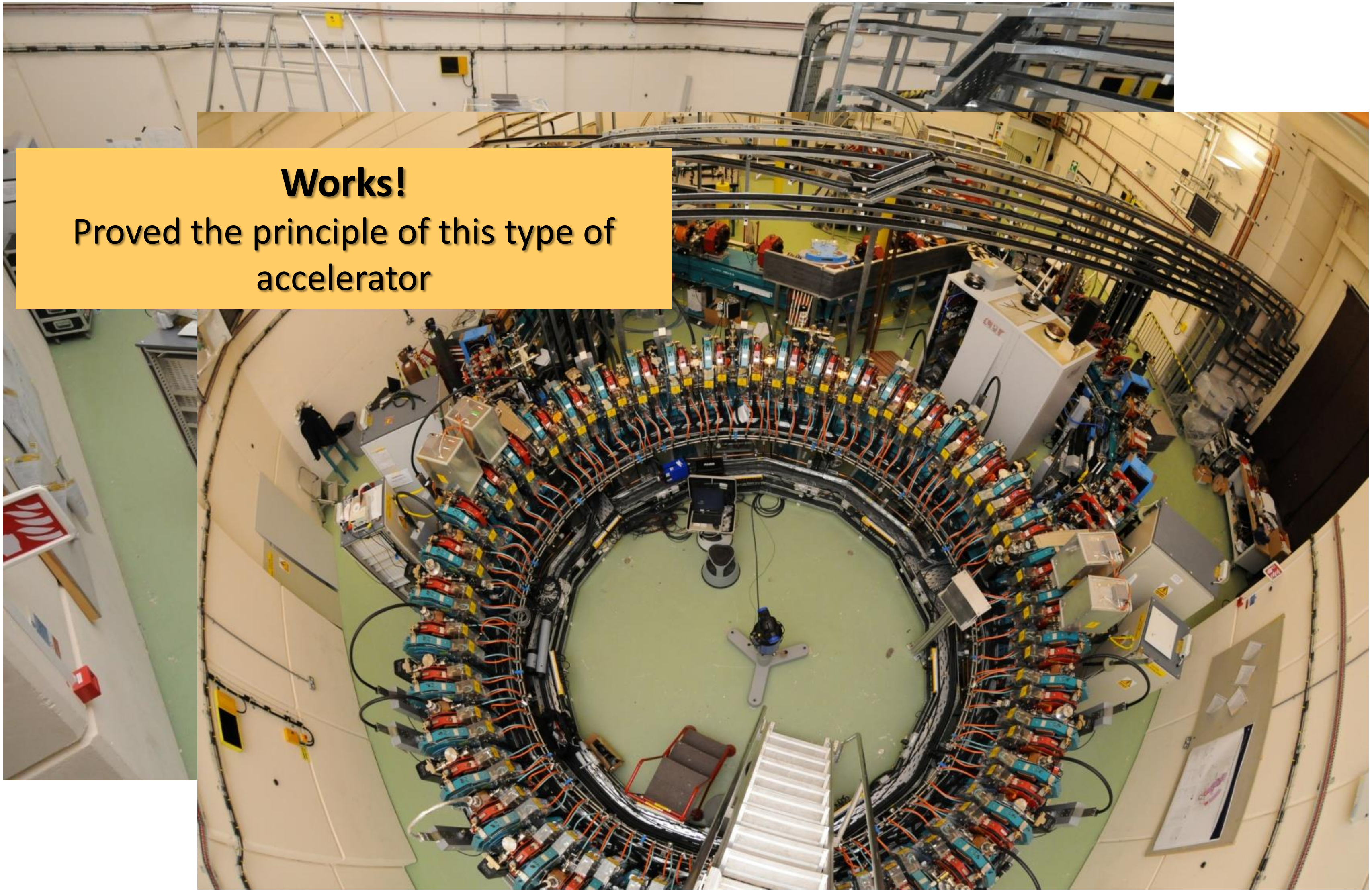
EMMA ring: beam makes
5 to 100+ turns in this

Section of ALICE



Proof-of-principle: cheapest option!
Electron acceleration: 10 to 20 MeV
Built in DL
Now finished

EMMA



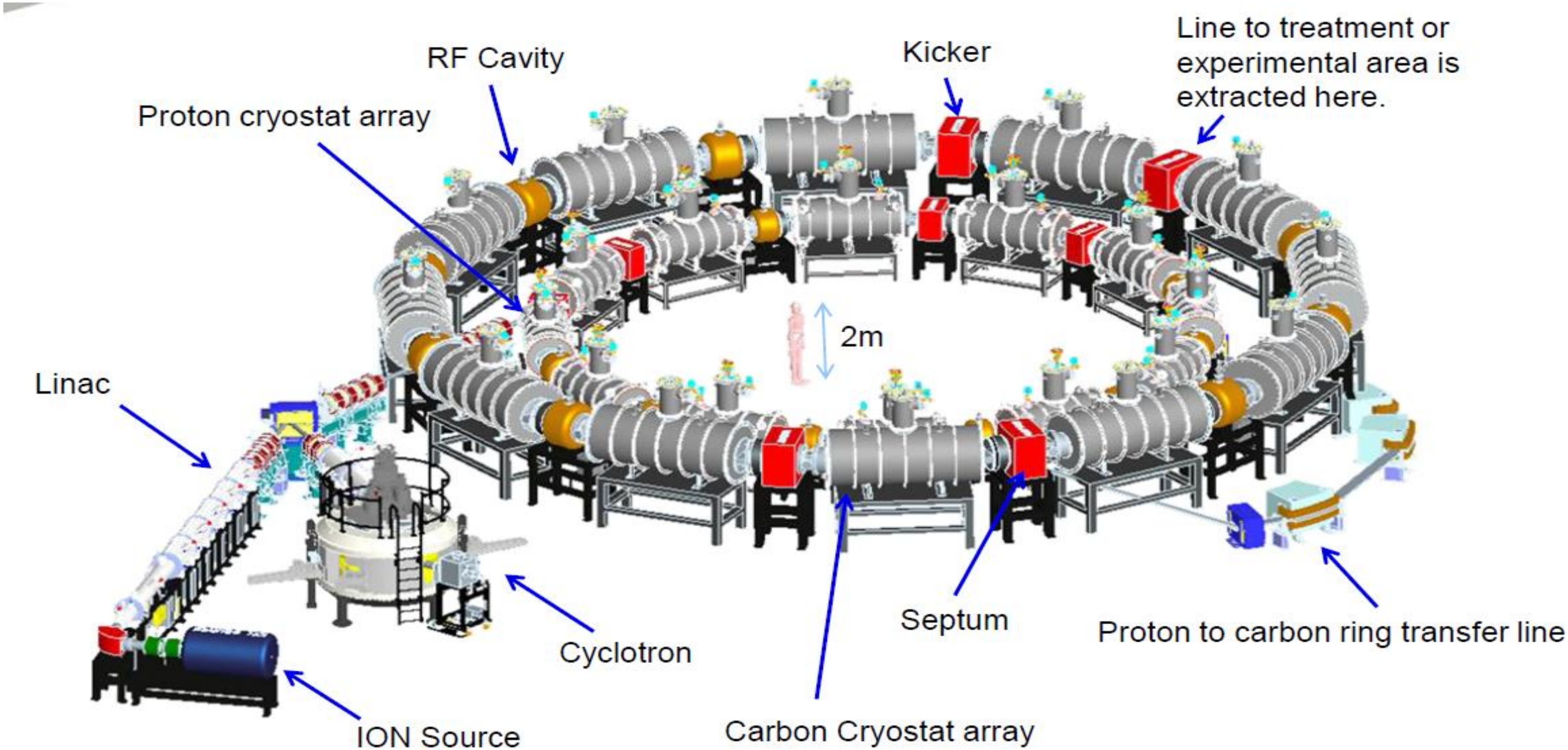
Works!

Proved the principle of this type of accelerator

PAMELA

- Being done in parallel to EMMA
- NS-FFAG carbon ion and proton therapy facility:
  - 250 MeV protons
  - 400 MeV/u carbon ions
  - gantry(ies), with spot scanning

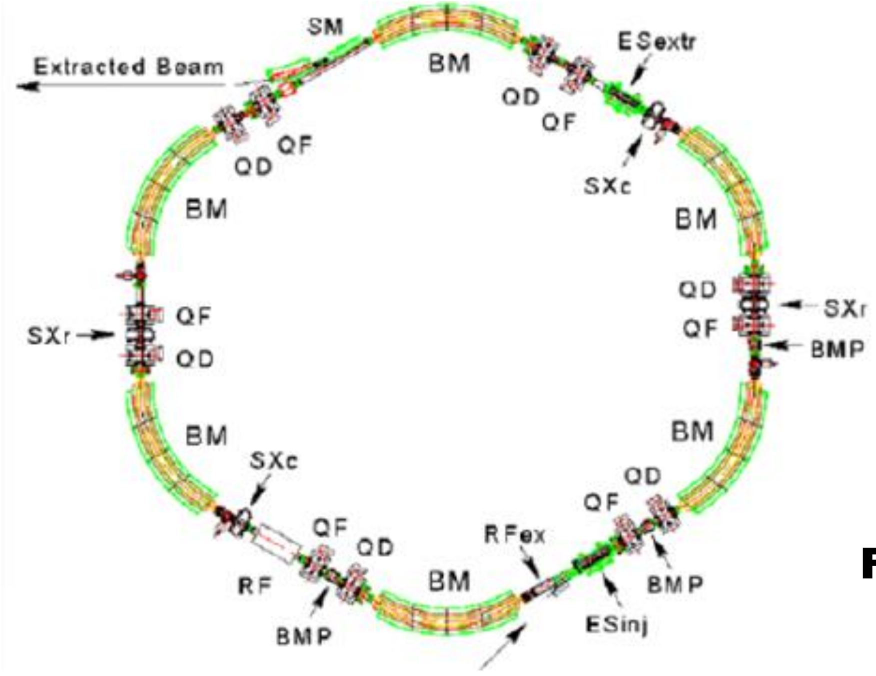
PAMELA

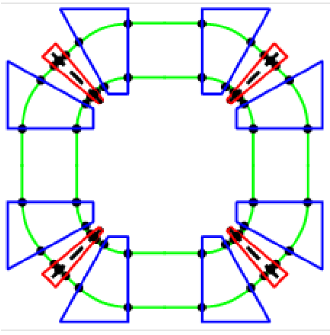


RF Cavity
Kicker
Line to treatment or experimental area is extracted here.
Proton cryostat array
2m
Linac
Cyclotron
ION Source
Septum
Proton to carbon ring transfer line
Carbon Cryostat array

More recent developments

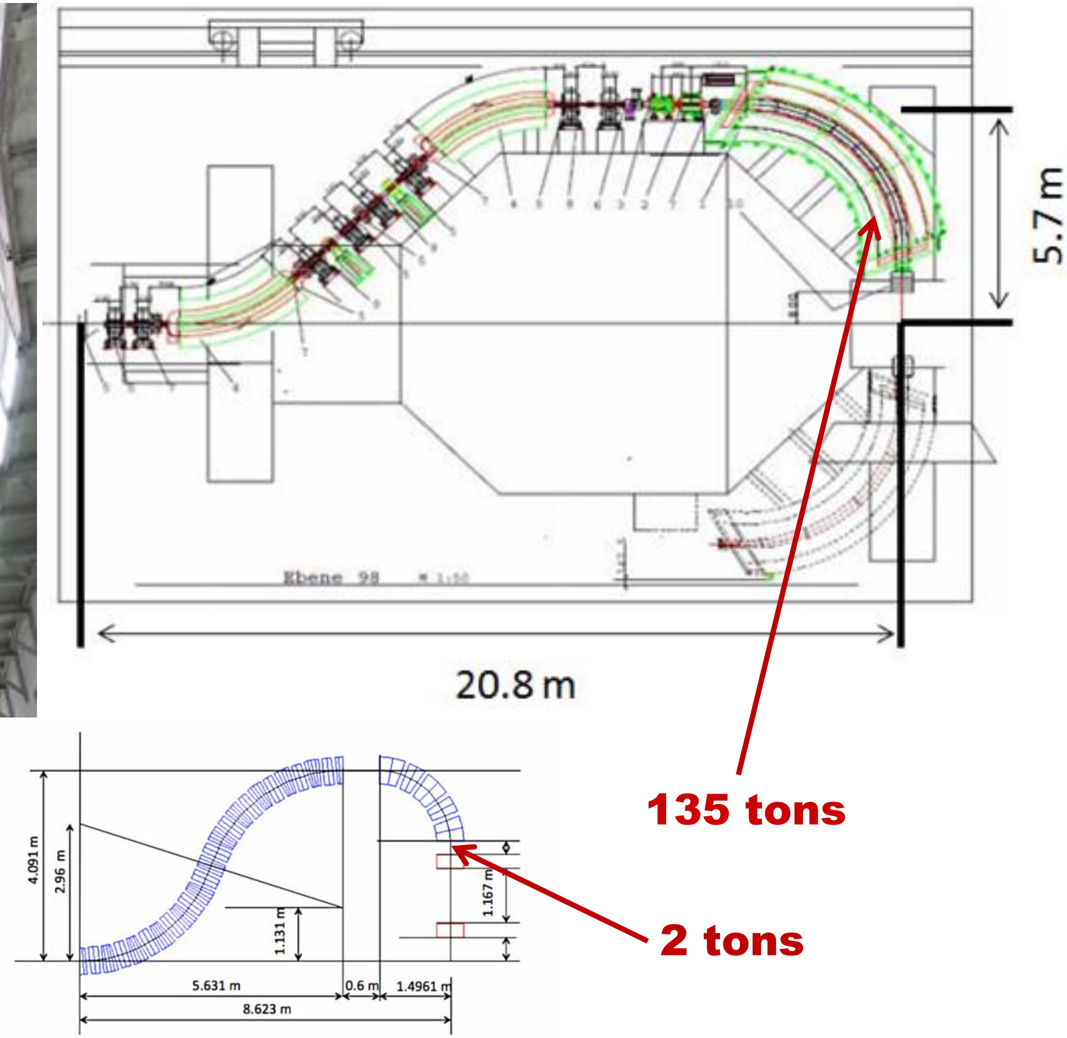
- New FFAG design
- More cyclotron-like
  - fixed RF frequency
  - very high beam currents
- Carbon therapy





Fixed Field Alternating Gradient accelerator

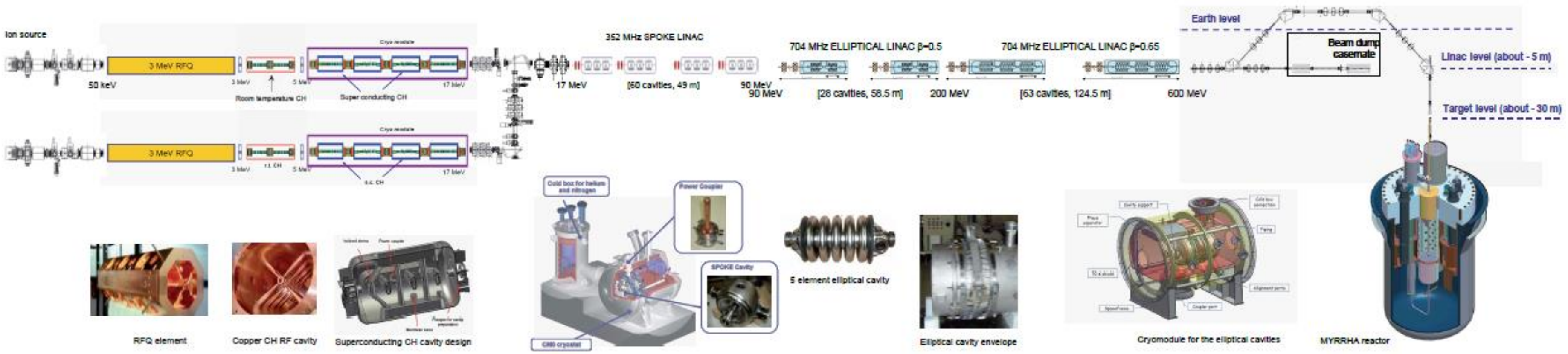
Carbon therapy

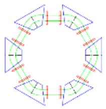


Others

- Radioisotope production
  - 10-30 MeV
  - 20mA: >20 times existing cyclotrons
- Accelerator Driven Systems (ADS)

MYRRHA project, Belgium





FFAG equivalent.
Much less well developed, but much cheaper to have redundancy

Conclusions

- Non-scaling FFAGs:
  - Unique form of accelerator
  - Combine features of cyclotrons and synchrotrons
  - More flexible than other circular accelerators
- World's first machine built in DL
- Being developed for:
  - particle physics: muon and proton acceleration
  - cancer therapy: with electrons (x-rays), protons, carbon ions, neutrons (BNCT)
  - energy generation: ADSR
- One of few places in accelerator R&D that UK has lead