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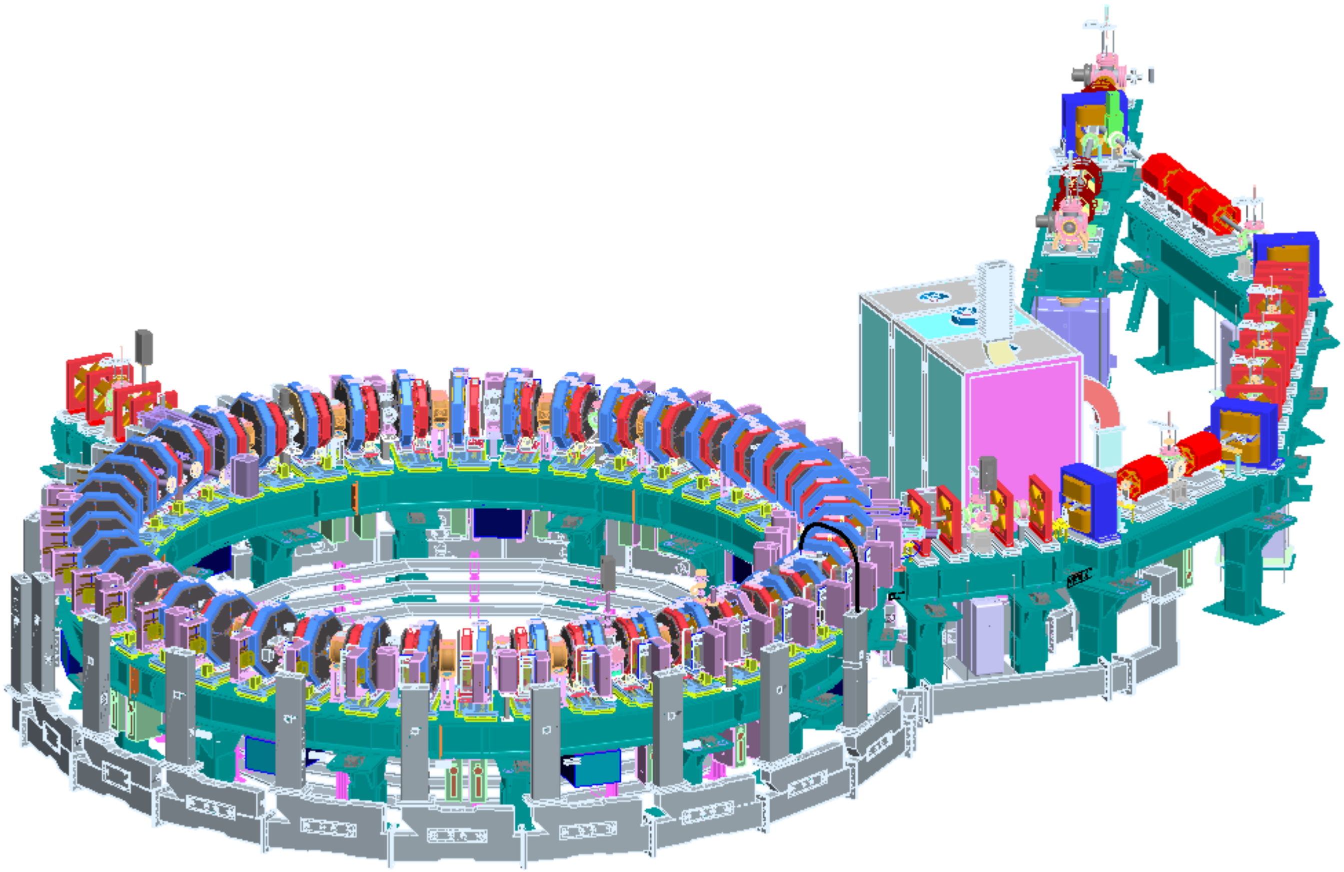
Applications of Accelerators

Rob Edgecock



Outline

- Introduction to particle accelerators
- Accelerator applications outside research
- Medical applications:
  - cancer therapy
  - radioisotope production
- "New" kind of accelerator created for particle physics
- Use for these applications

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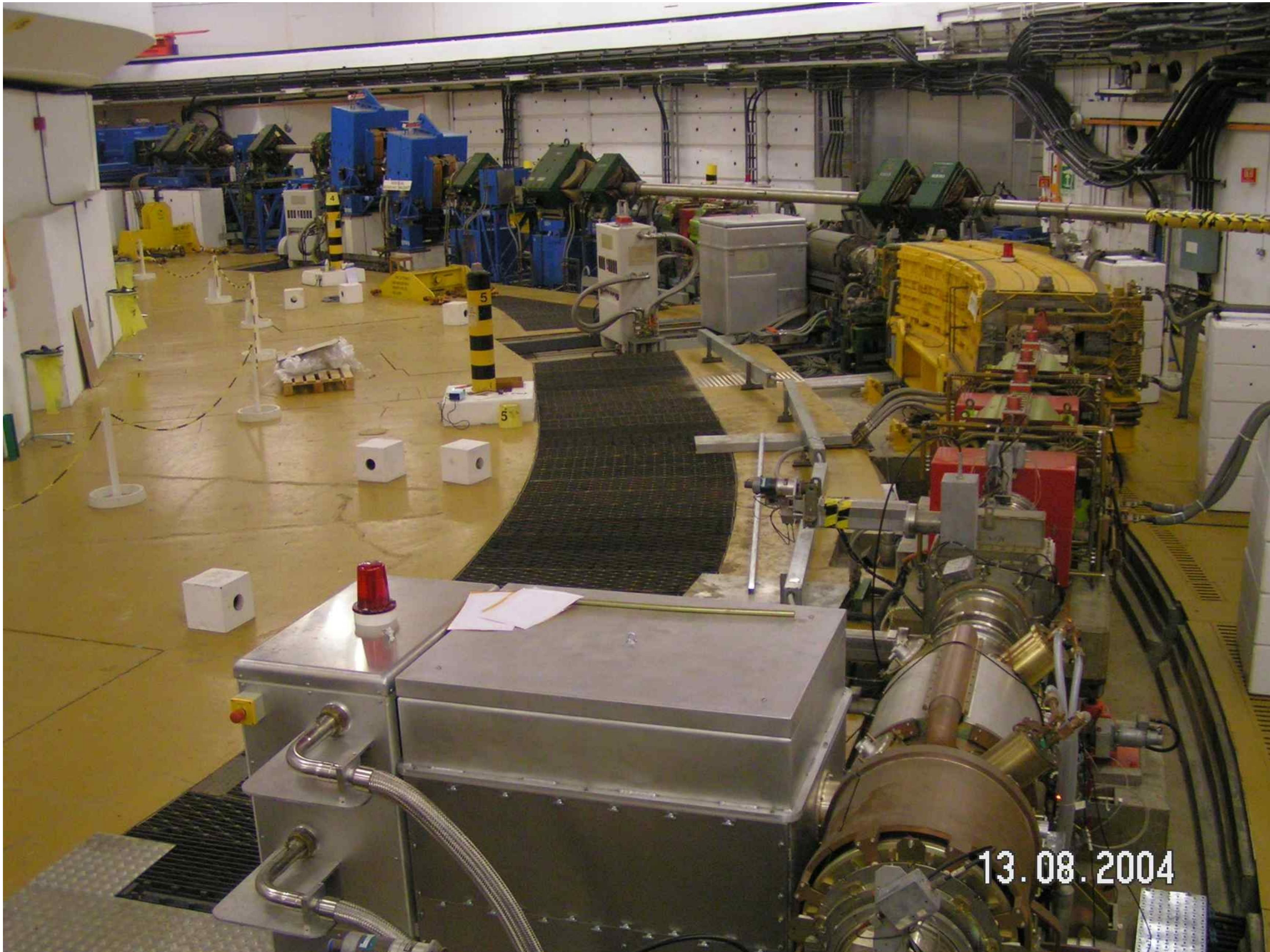
RAL


13.08.2004

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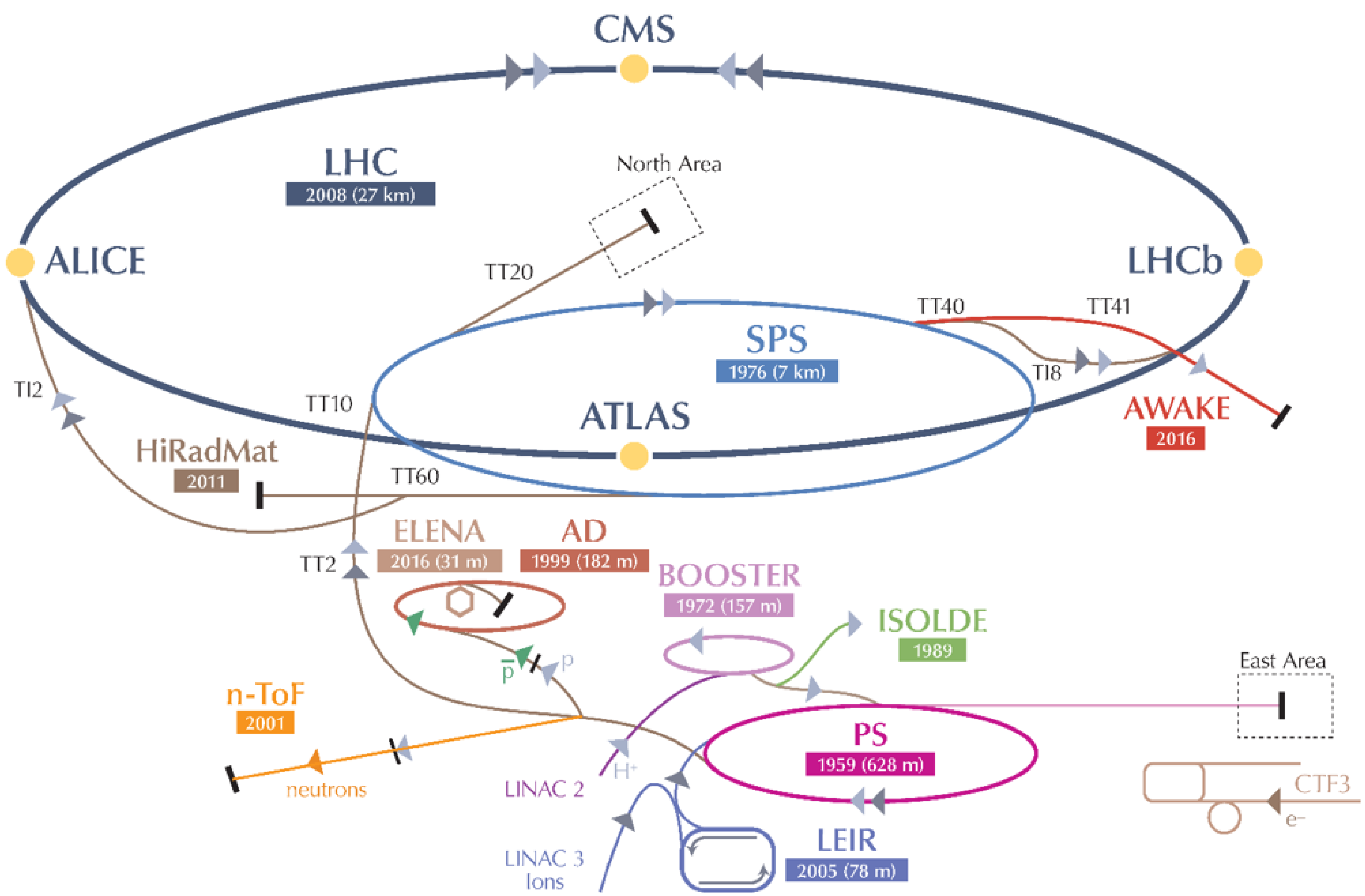
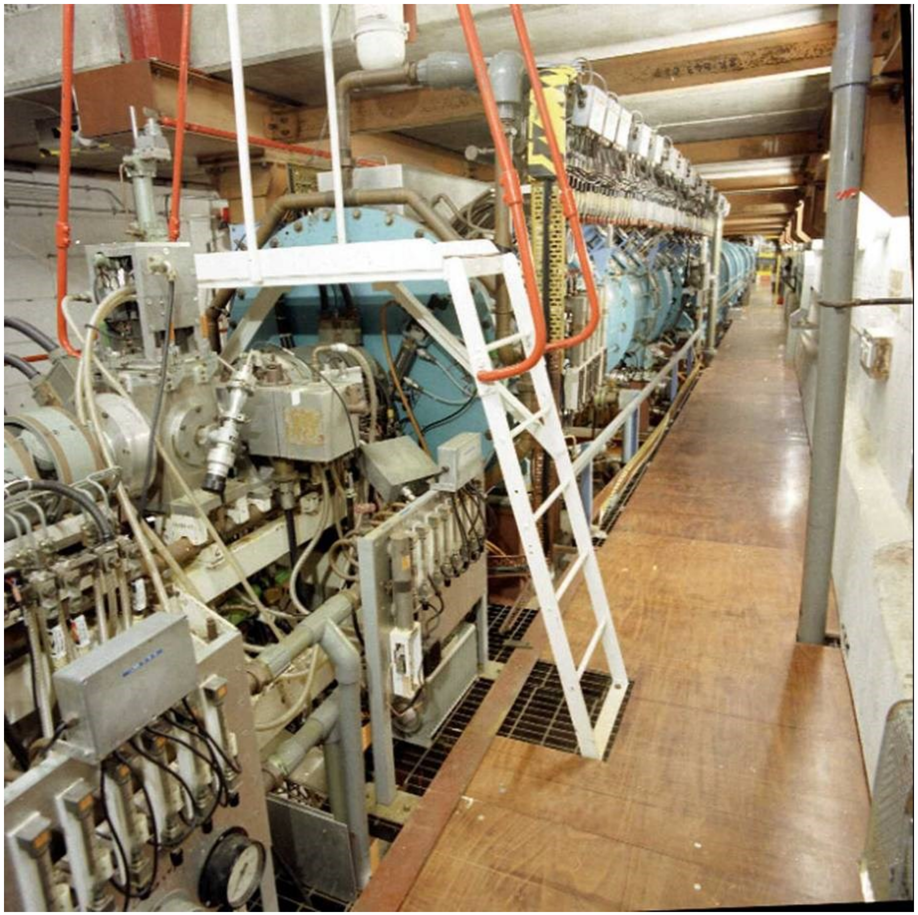
RAL

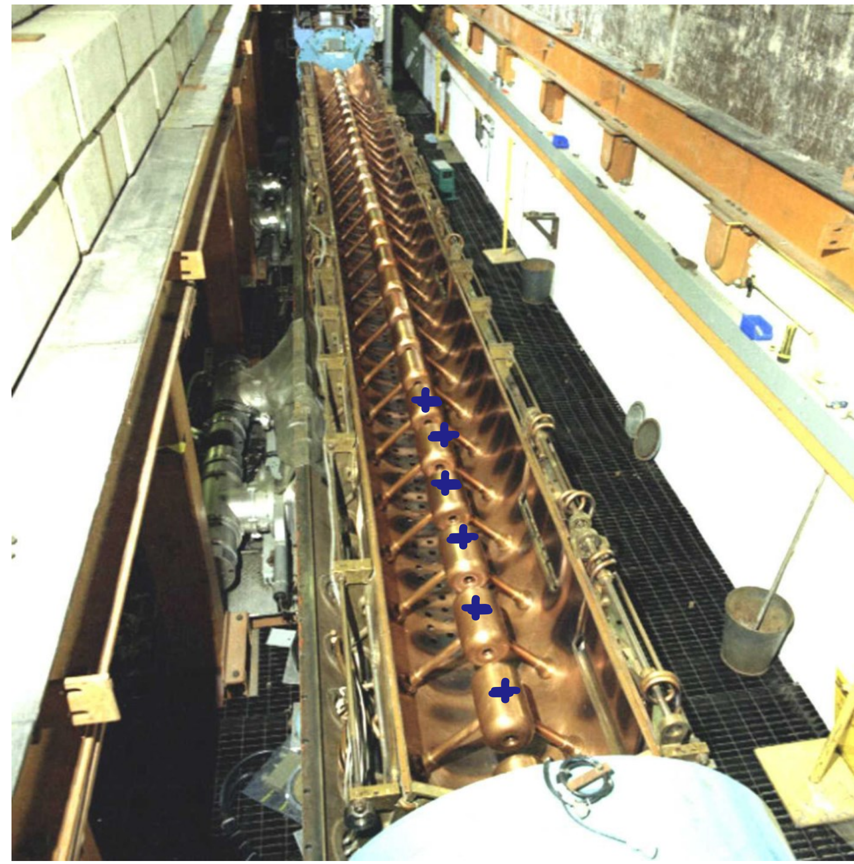
CERN

CERN's Accelerator Complex



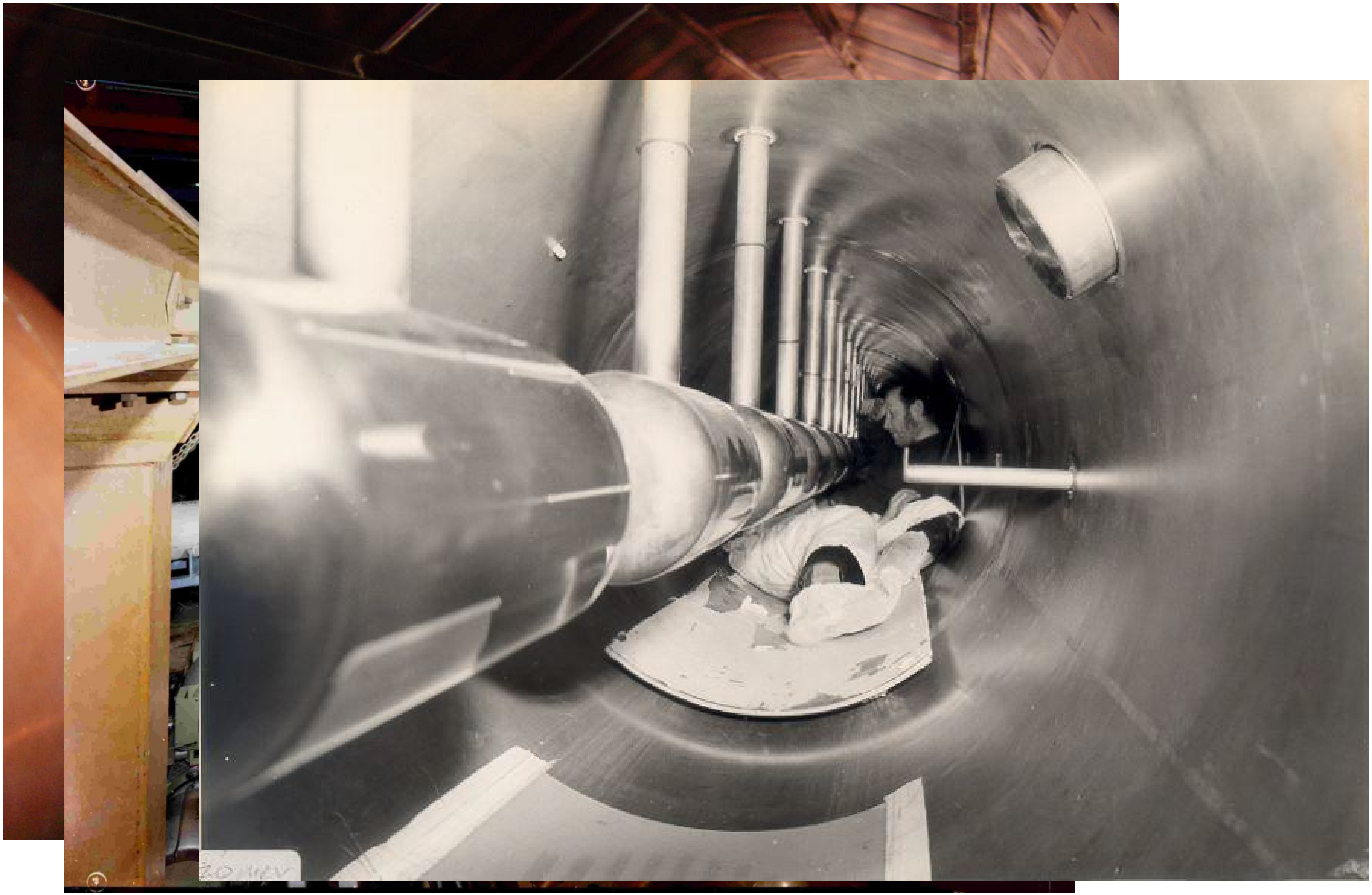
Linear Accelerators





Acceleration via electric fields
AC frequency in the RF range

Linear Accelerators

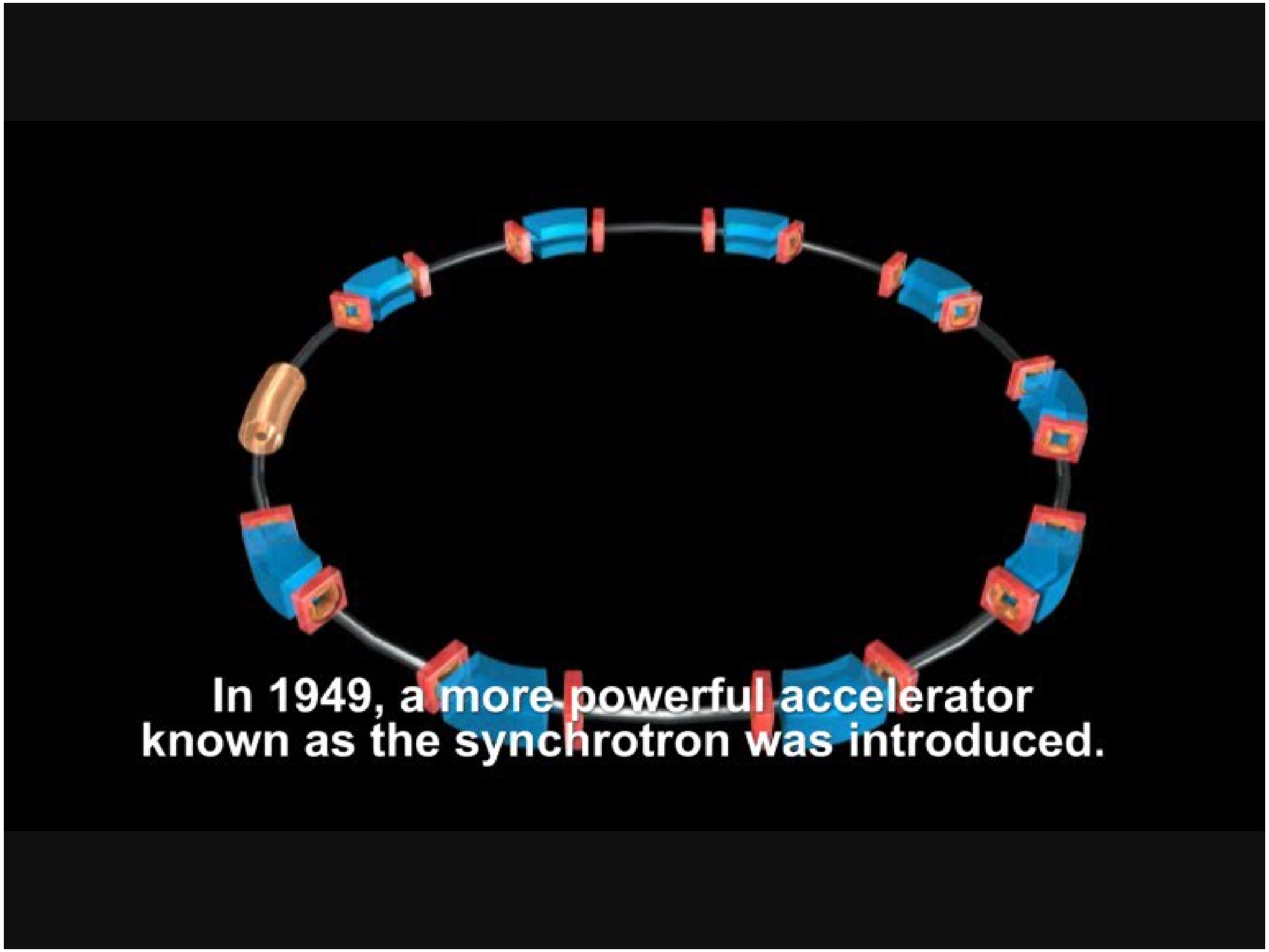


Linear Accelerators

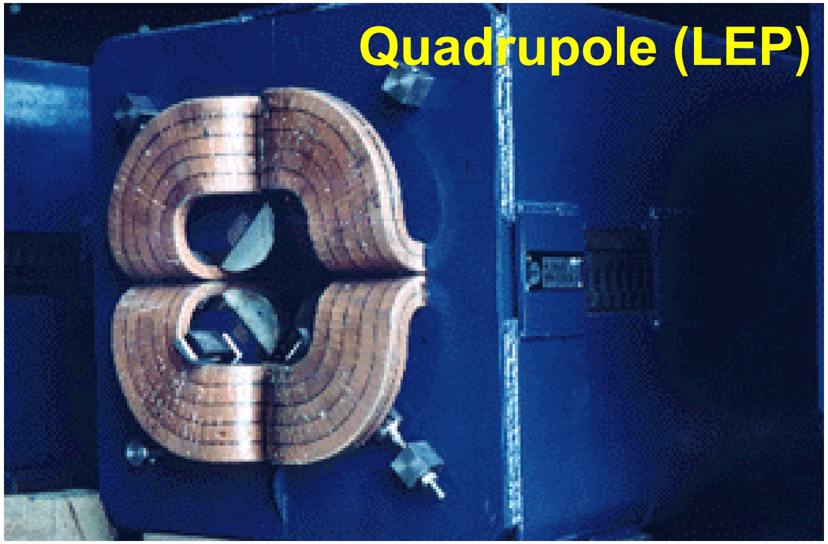
- Advantages:
  - fixed RF frequency
  - fixed magnetic fields
  - easy to operate
  - fairly reliable
  - good for non-relativistic particle
- Disadvantages:
  - each component used once per pass
  - long for high energies
  - expensive at higher energies

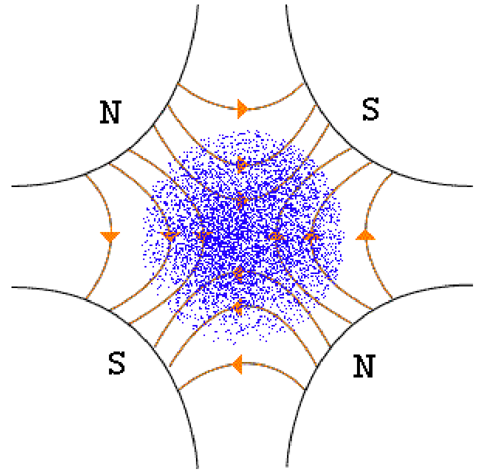
Synchrotrons

Circular accelerators:

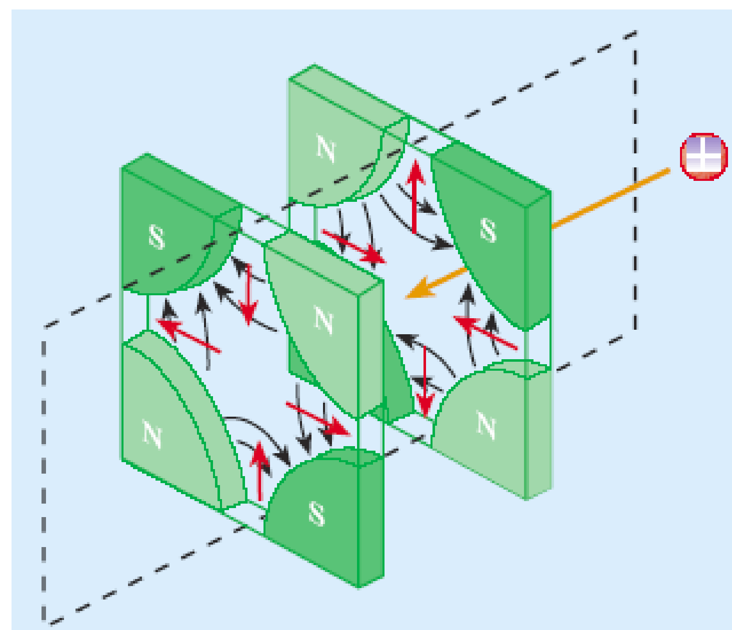


Strong Focussing





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



Strong Focussing

Strong Focussing

Main Dipoles	MB	1232	twin
Lattice quadrupoles	MQ	392	twin
Lattice sextupoles	MS	688	single
Lattice Octupoles	MO	168	twin
Skew quadrupoles	MQS	32	twin
Arc skew sextupoles	MSS	64	single
Tuning trim quadrupoles	MQT	160	twin
Octupole spool pieces	MCO	1232	single
Decapole spool pieces	MCD	1232	single
Sextupole corrector (b3) in MBA & MBB (spool piece corrector)	MCS	2464	single
Insertion region long trim quads	MQTLI	36	twin
Arc dipole corrector	MCBH	376	single
Arc dipole corrector	MCBV	376	single
Twin aperture separation dipole in IR (194mm). D4	MBRB	2	twin
Twin Aperture Separation dipole in IR(188mm). D2	MBRC	8	twin
Single Aperture Separation dipole. 1 MBRS magnet on each beam - one cryostat (D3 in IR4)	MBRS	4	single
Single aperture separation dipole. D1 in IR2 and IR8	MBX	4	single
Twin aperture warm dipole. D3 and D4 in IR3 and IR7	MBW	20	twin
Single aperture warm dipole. D1 in IR1 and IR5 (6 each side)	MBXW	24	single
Matching correction dipole	MCBCH	80	
Matching correction dipole	MCBCV	80	
Inner Triplet Horizontal dipole corrector,	MCBXH	24	single
Inner Triplet vertical separator	MCBXV	24	single
Single aperture, horizontal, warm dipole corrector	MCBWH	8	
Single aperture, vertical, warm dipole corrector	MCBWV	8	
Matching section dipole orbit corrector	MCBYH	44	single
Matching section dipole orbit corrector	MCBYV	44	single
Skew octupole spool-piece (a4) associated to MQSX in MQSXA	MCOSX	8	single
Octupole spool-piece (b4) associated to MQSXA	MCOX	8	single
Quadrupole in the insertions (3.4 m)	MQM	46	twin
Quadrupole in the insertions (4.8 m)	MQML	36	twin
Wide aperture quadrupole in the insertions, twin aperture	MQY	24	twin
Quadrupole in the insertions (2.4 m)	MQMC	12	twin
Twin aperture warm quadrupole in IR3 and IR7.	MQWA	40	twin
Twin aperture warm quadrupole in IR3 and IR7.	MQWB	8	twin
Inner triplet quadrupole, single aperture (Q1, Q3)	MQXA	16	single
Inner triplet quadrupole, single aperture (Q2)	MQXB	16	single
Skew sextupole spool-piece (a3) associated to MQSX in MQSXA	MCSSX	8	single
Sextupole spool-piece (b3) associated to MCBXA	MCSX	8	single
	MQRL	4	twin
	MQR	4	twin
Dodecapole spool-piece (b6) associated to MCBXA	MCTX	8	single
Skew quadrupole (a2) in MQSXA	MQSX	8	single
	MCBWB	1	
	MU	8	

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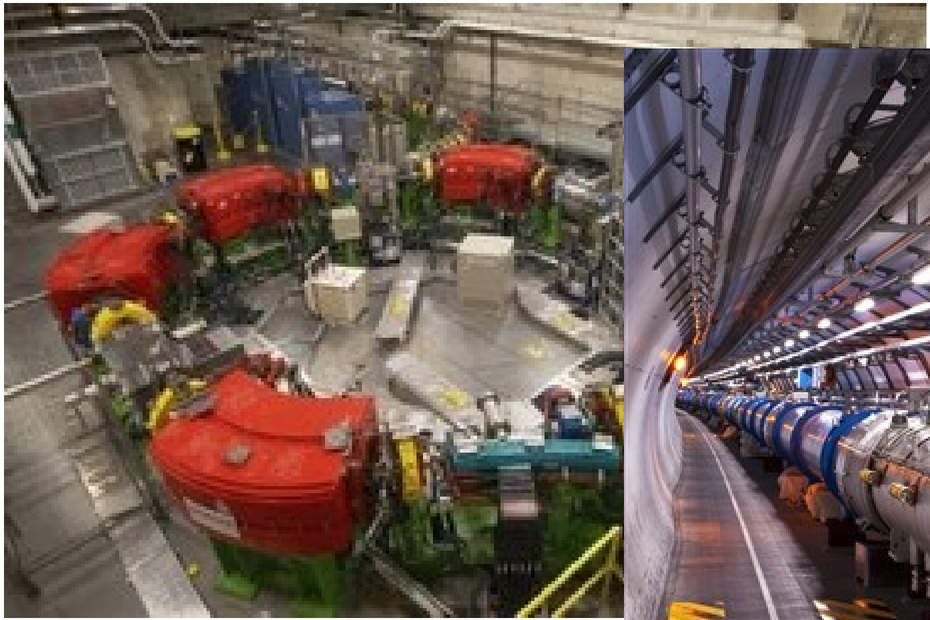
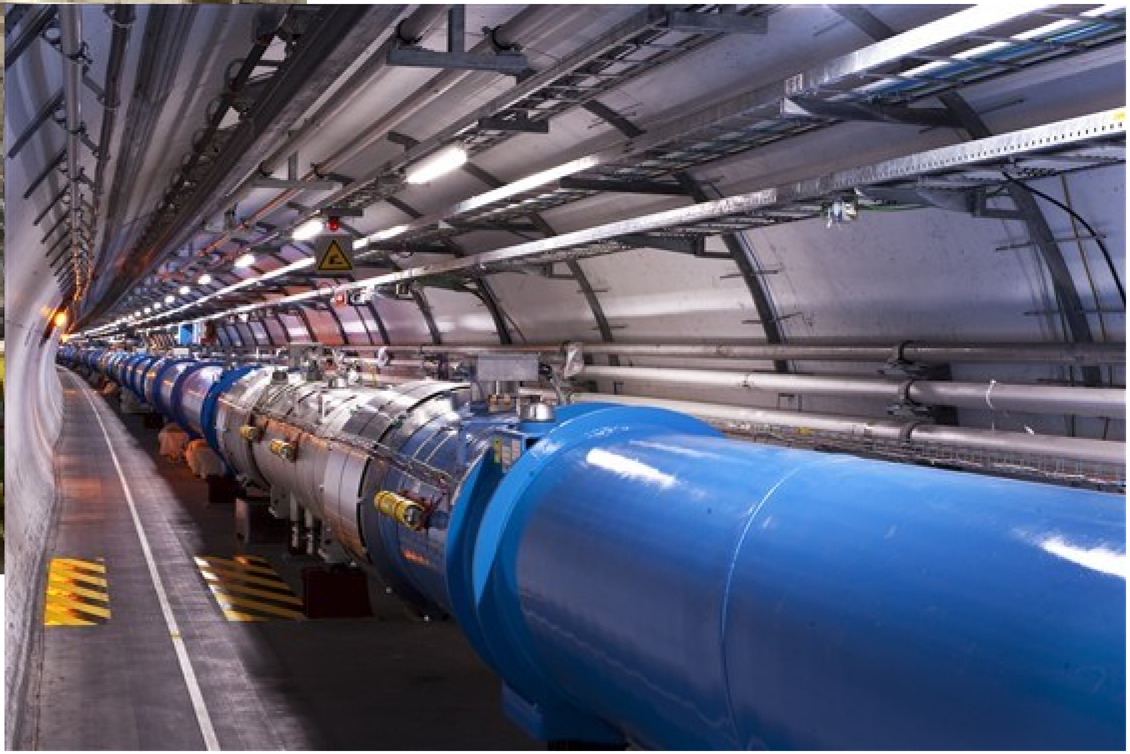
Synchrotrons

Circular accelerators





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Synchrotrons

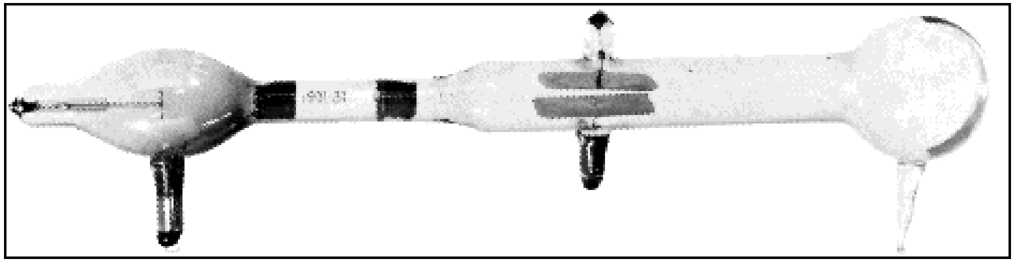
- Advantages:
  - very high energies possible
  - very good beam control
  - small machine aperture
- Disadvantages:
  - big
  - expensive
  - pulsed
  - pulsed magnets
  - variable frequency RF
  - not so easy to operate

Rest of the World

- More than 40000 accelerators in use
- About half $<$ 5 MeV
- Nearly all of rest $<$ 20 MeV
- Used for a variety of applications
- Three types of accelerator
  - electrostatic
  - linacs
  - cyclotrons

Electrostatic Accelerators

- Use a DC electric field for acceleration
- Various types
- Main limitation: electrical breakdown

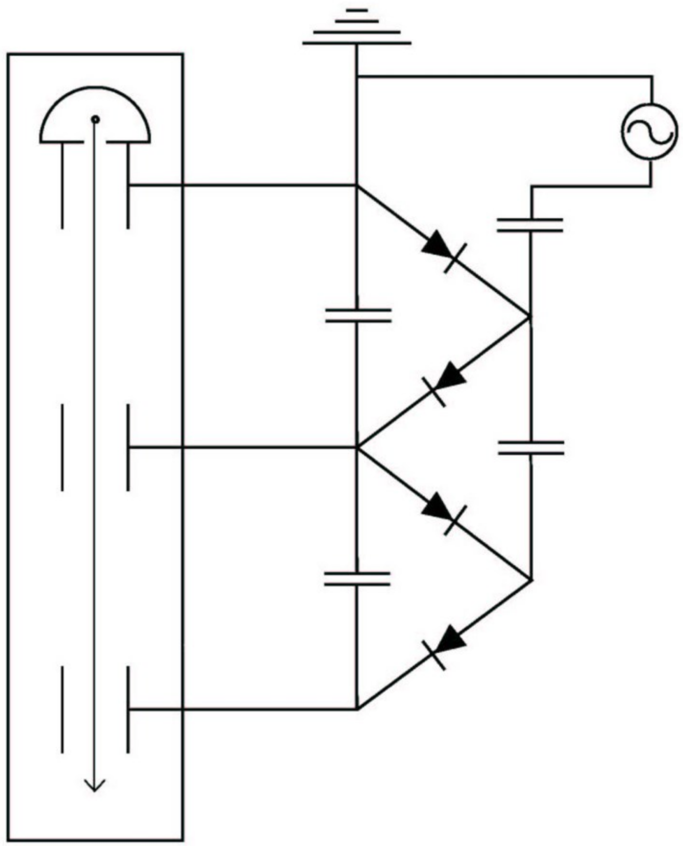


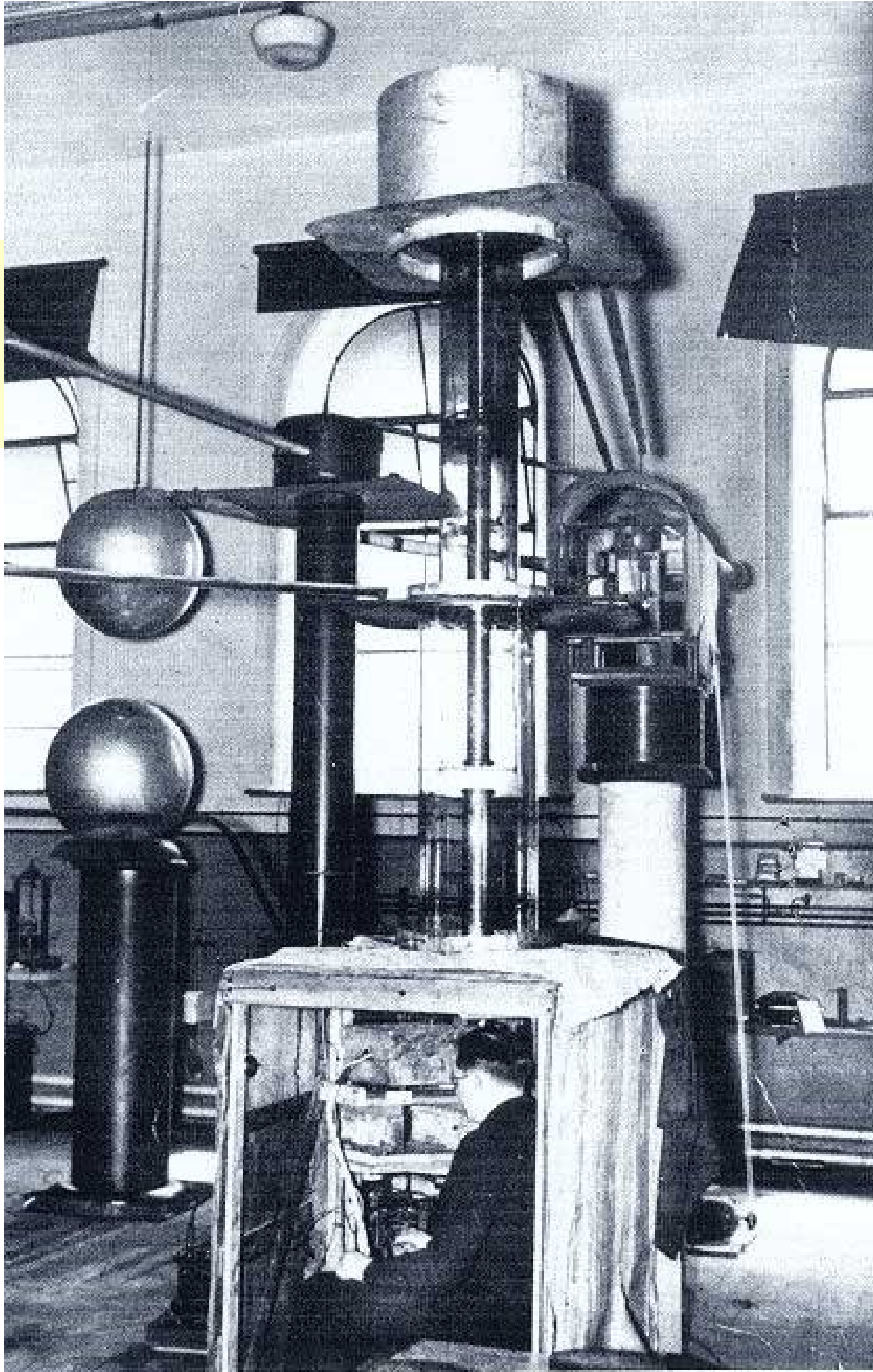
1897 – J.J. Thomson

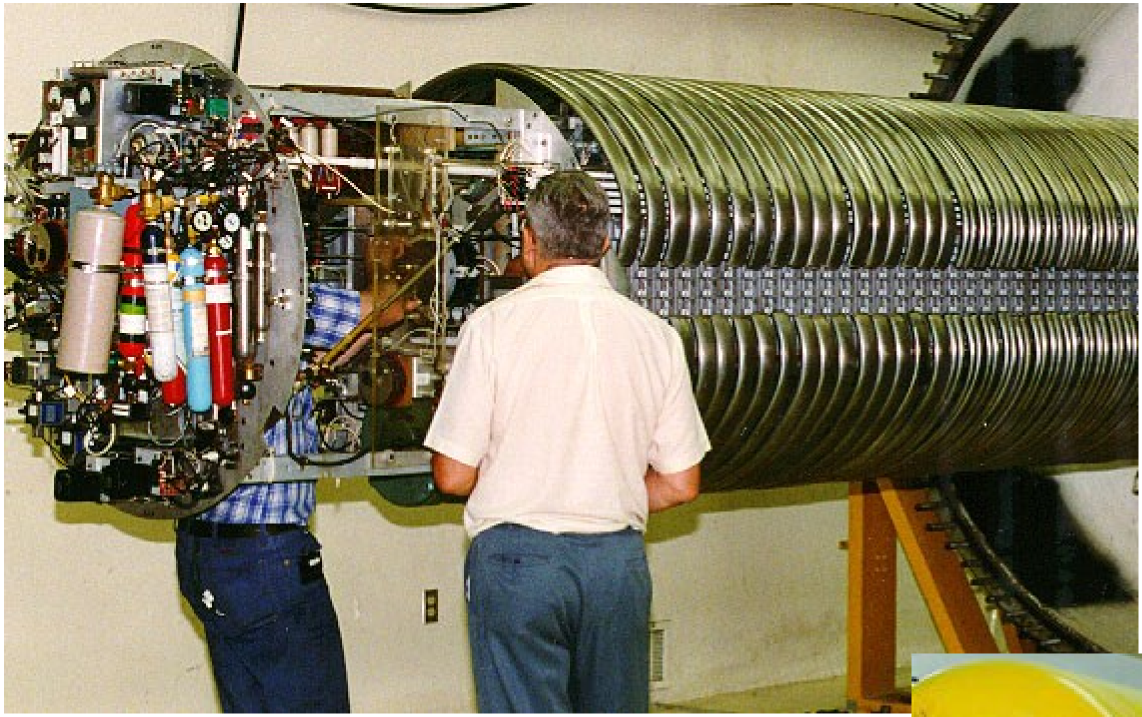
Cathode ray tube

- Cockcroft Walton ~voltage multiplier
- Van der Graaff
- Tandem

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

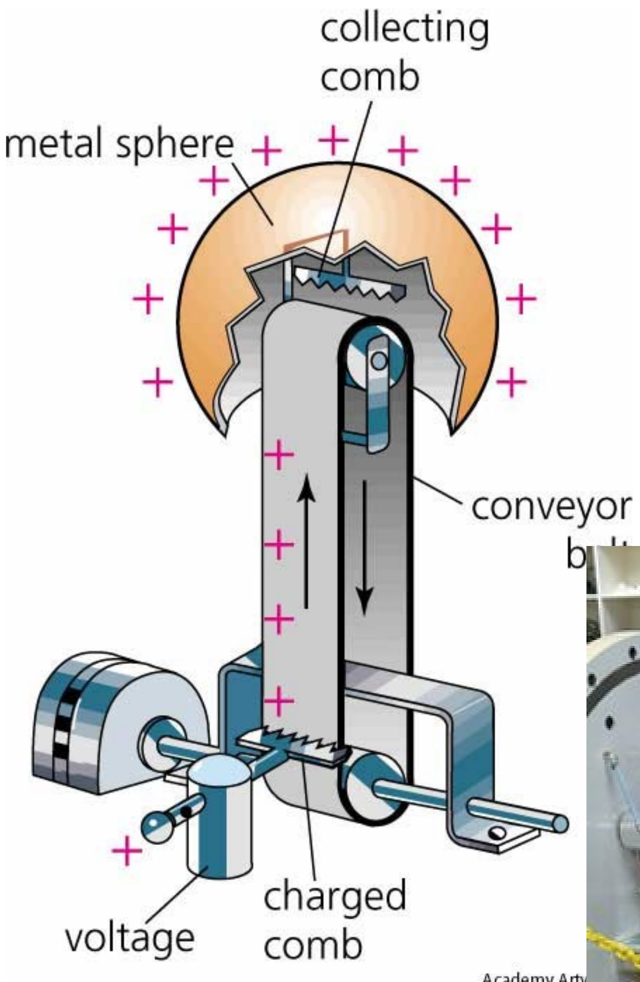


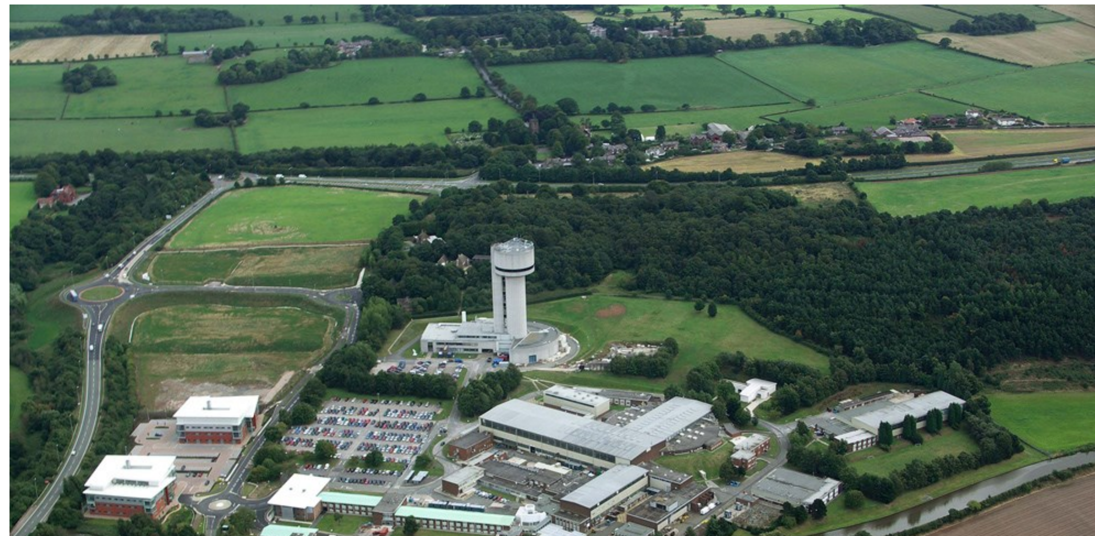




Dynamitron

Electrostatic Accelerators





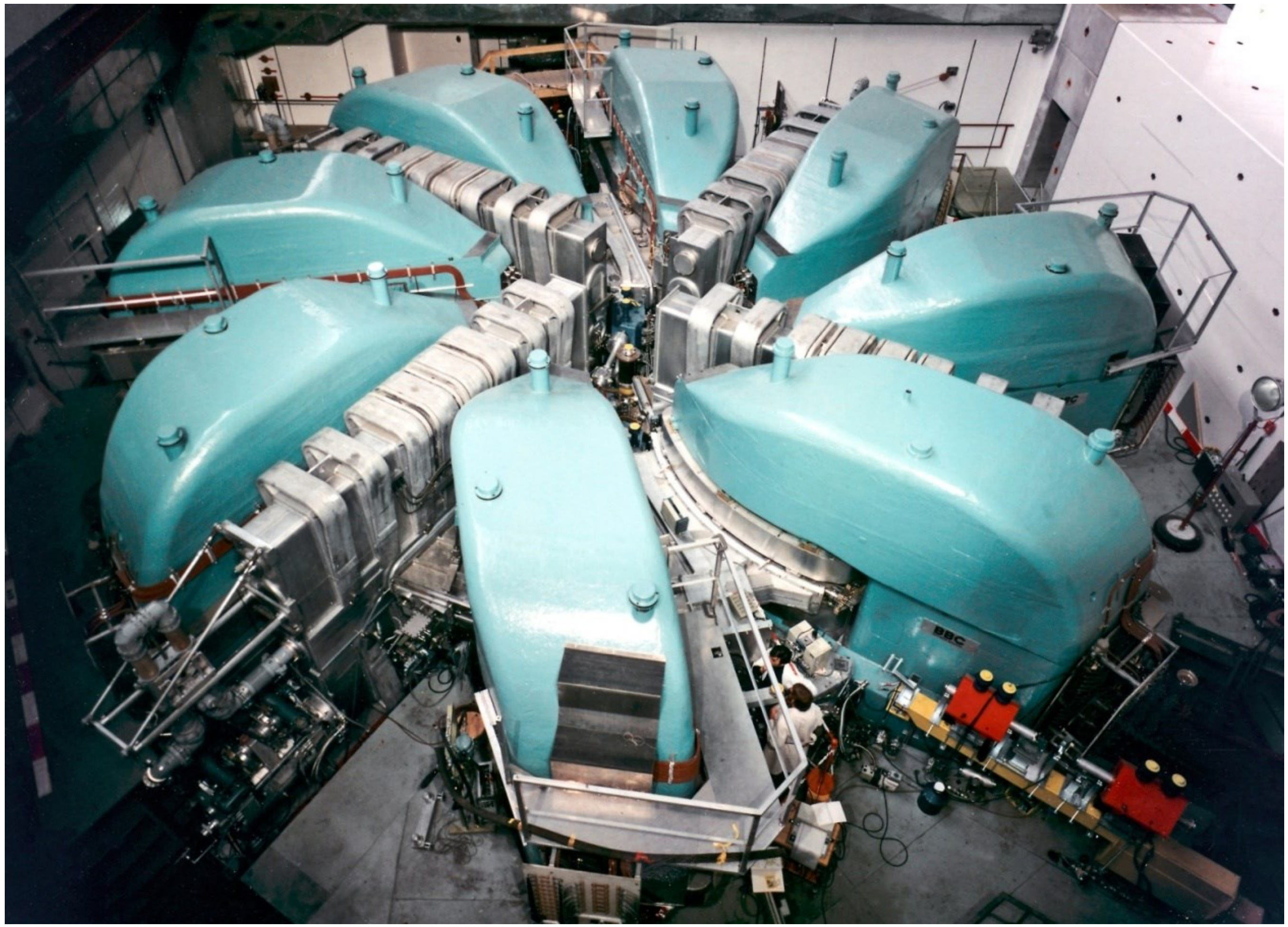
Electrostatic Accelerators

- Advantages:
  - DC
  - large beam currents possible
  - easy to operate
  - very efficient
  - reliable
- Disadvantages:
  - limited beam energy
  - high voltages

Cyclotrons

Cyclotrons

PSI cyclotron
600MeV



Cyclotrons

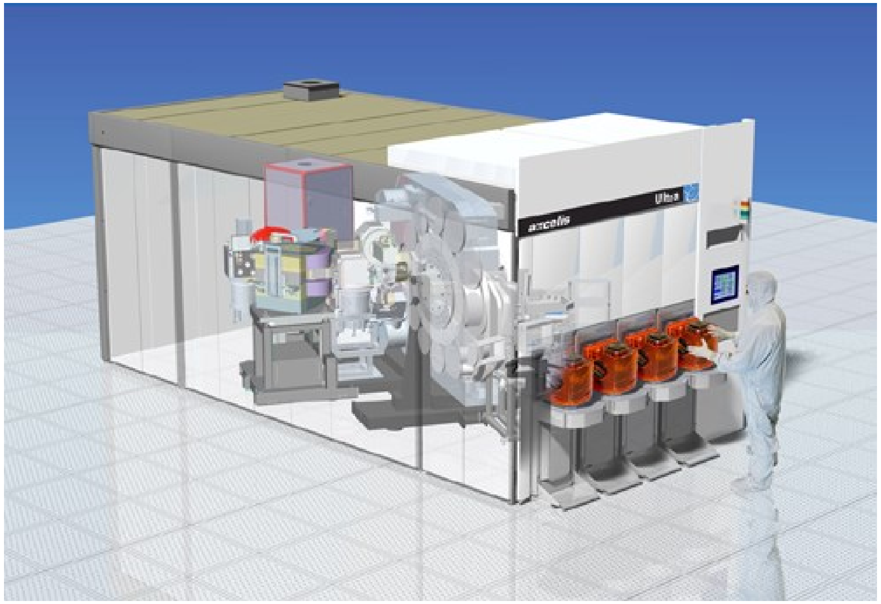
- Advantages:
  - CW
  - fairly large beam currents possible
  - easy to operate
  - fairly efficient
  - reliable
- Disadvantages:
  - fixed beam energy
  - highish beam losses

Accelerator Applications

- Accelerators created for Particle Physics
- Many developments driven by PP
- Now used for other applications
  - >40000 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

Ion implantation: making better semi-conductors
>10000

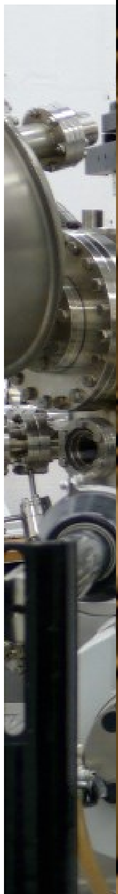


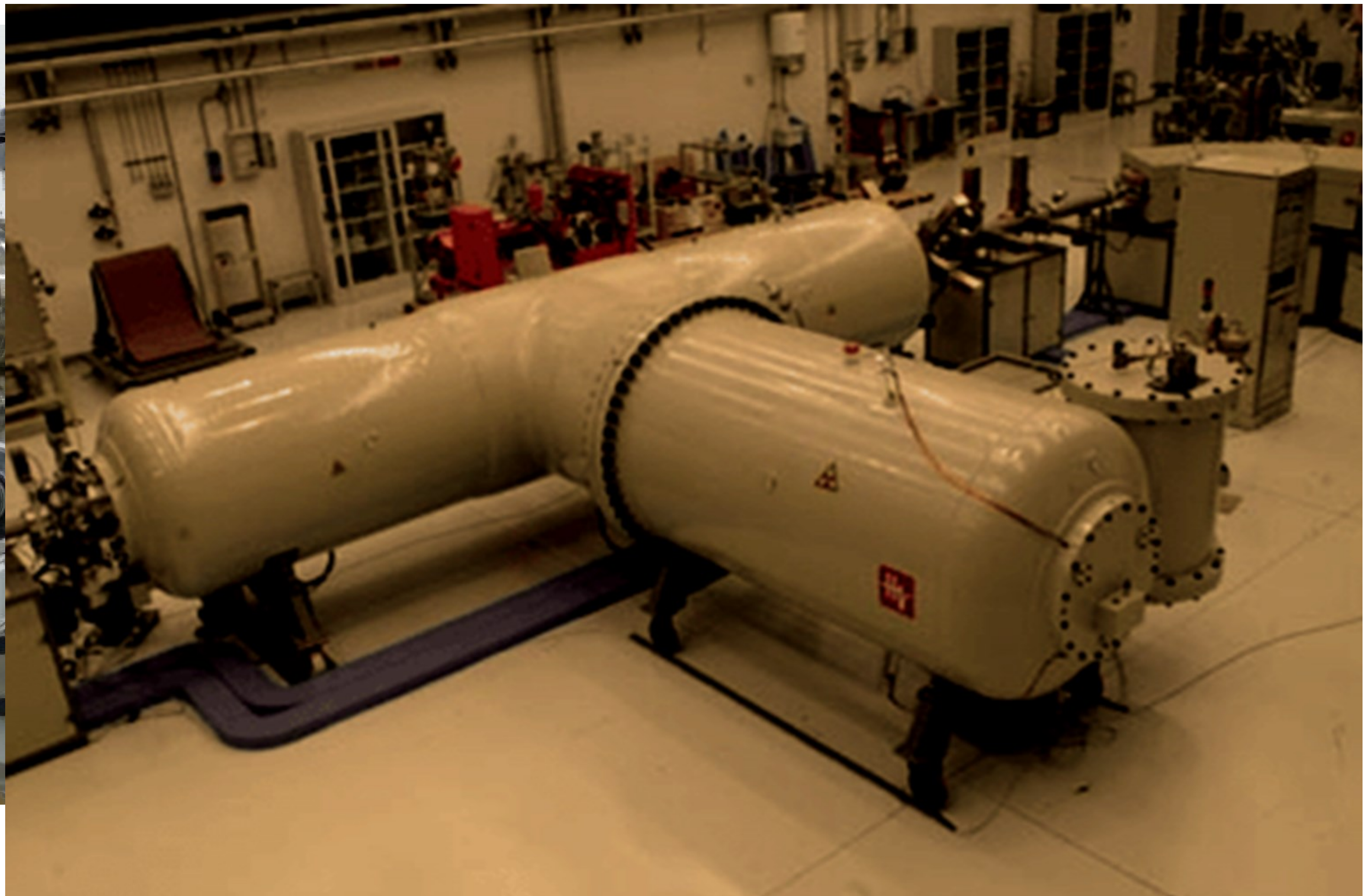
Electrostatic accelerators – usually up to few 100 keV
maximum around 4 MeV
high current possibility helpful

Applications

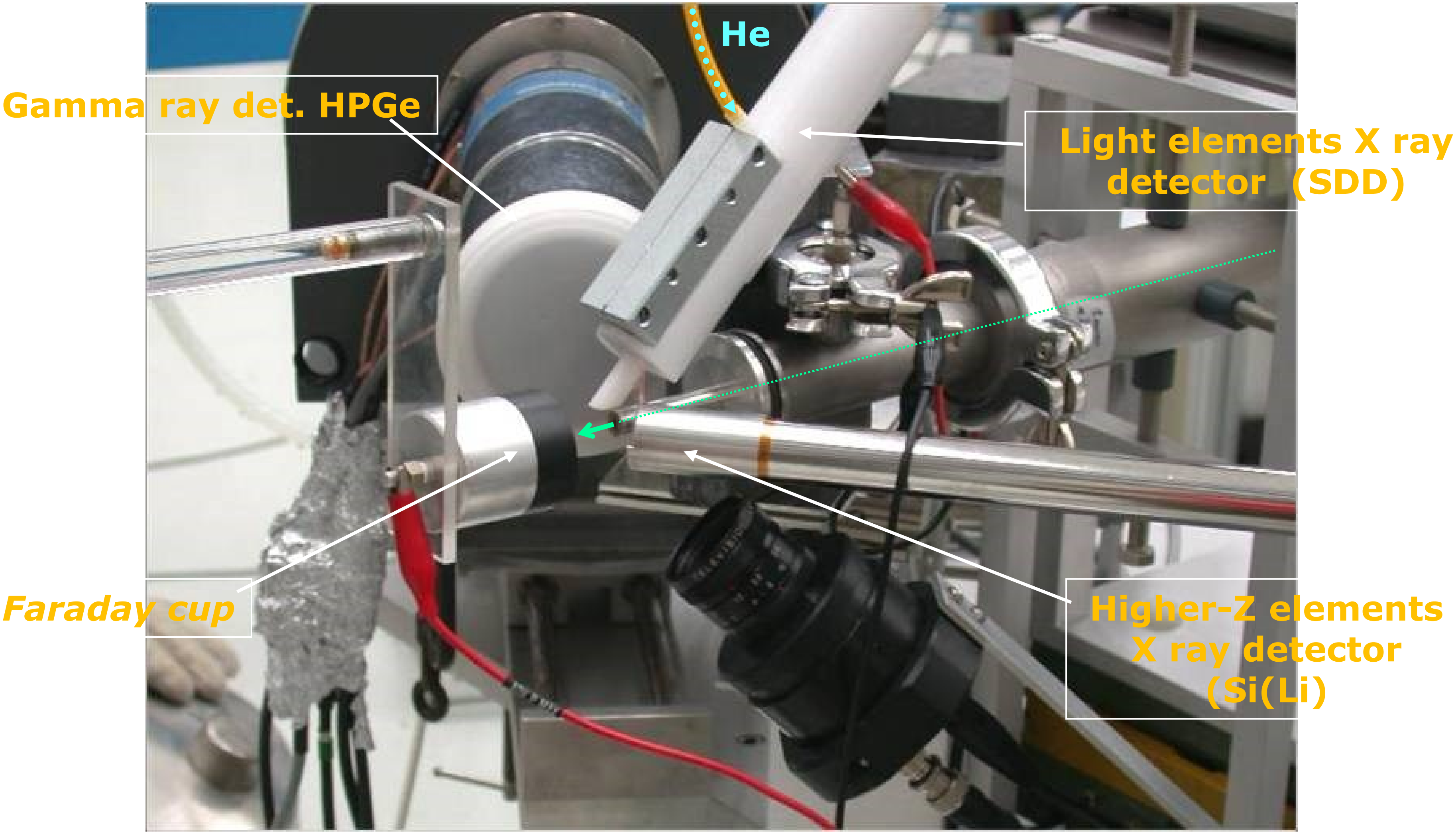
Ion beam analysis: determining material structure and composition

>1500

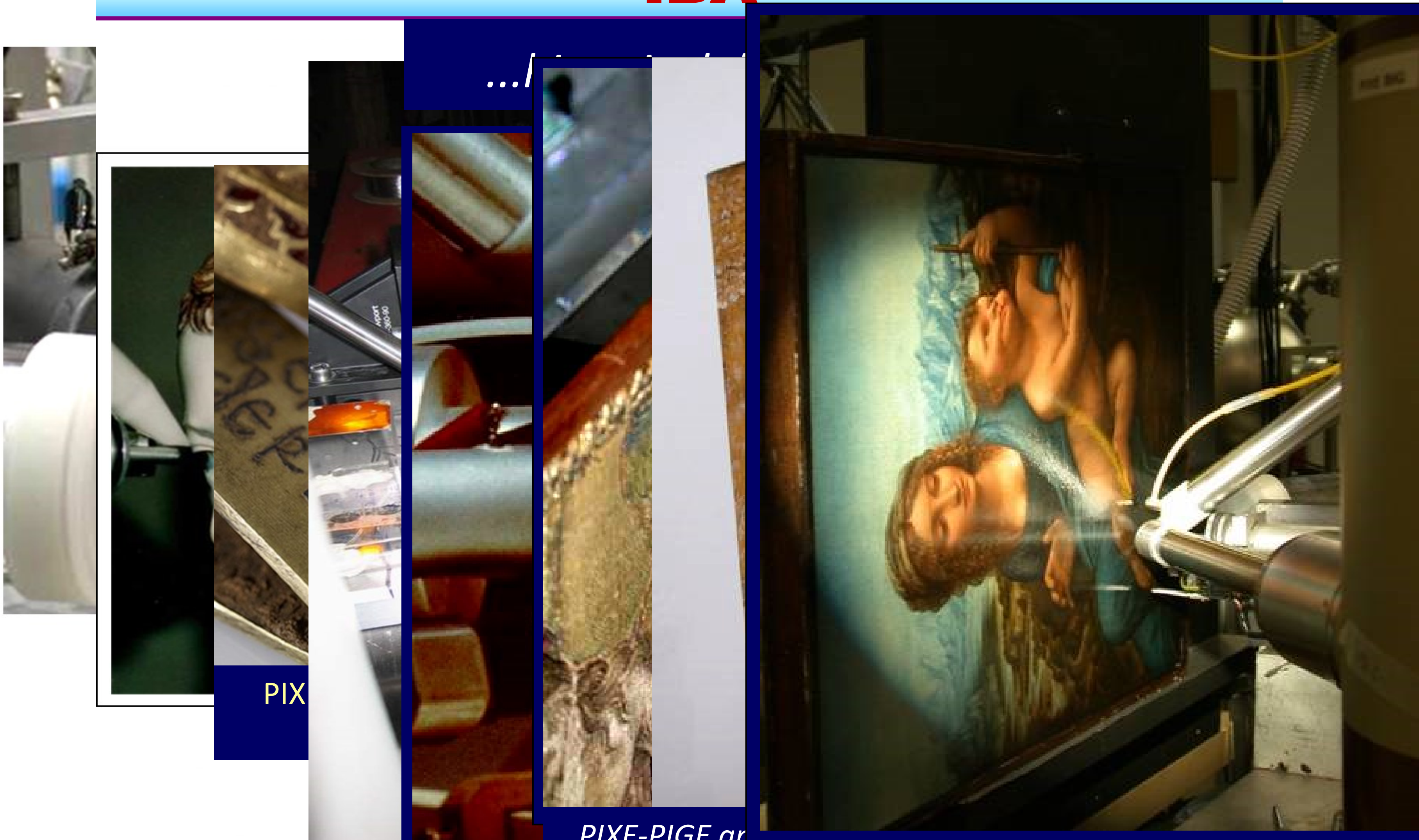




IBA


He
Gamma ray det. HPGe
Light elements X ray detector (SDD)
Faraday cup
Higher-Z elements X ray detector (Si(Li))

IBA



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

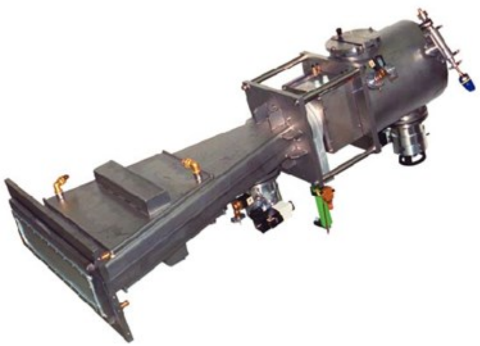
Low Energy Electron Beams

>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

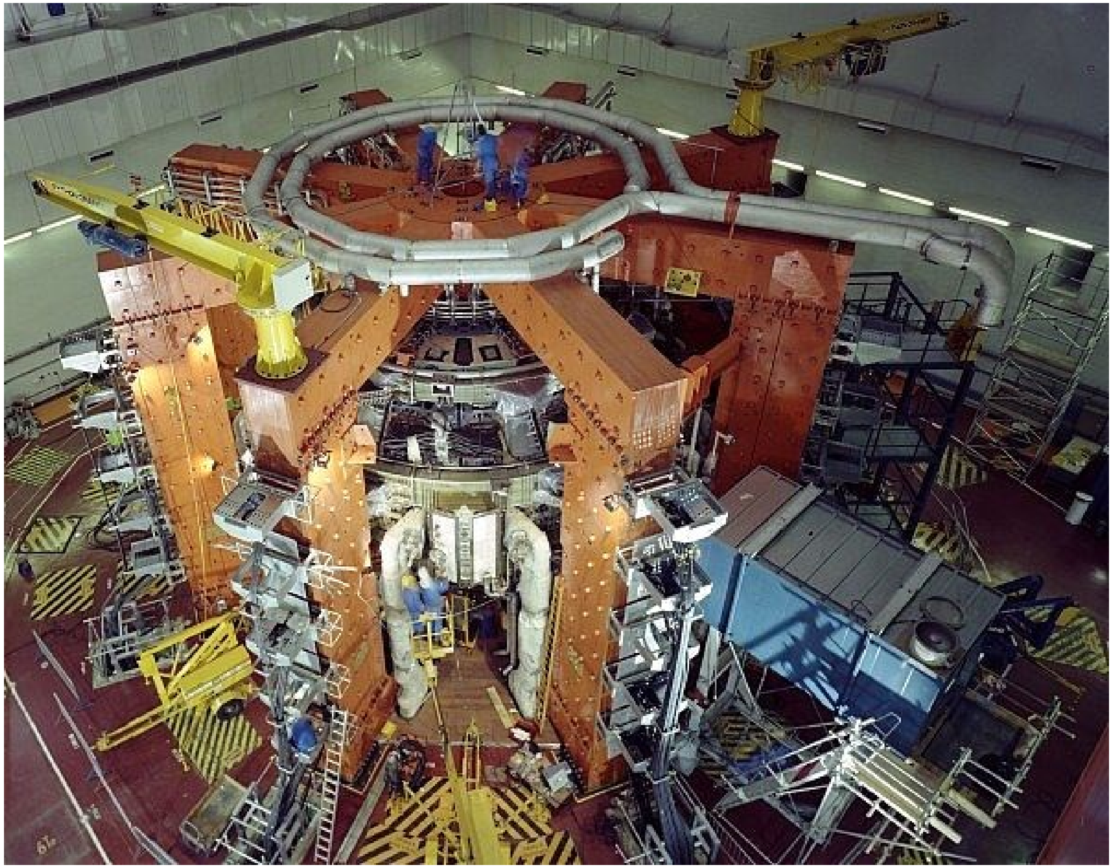
1 MeV for water treatment

10 MeV IBA Rhodotron

Low Energy Electron Beams

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

Energy



Fusion:
Plasma heating

Energy

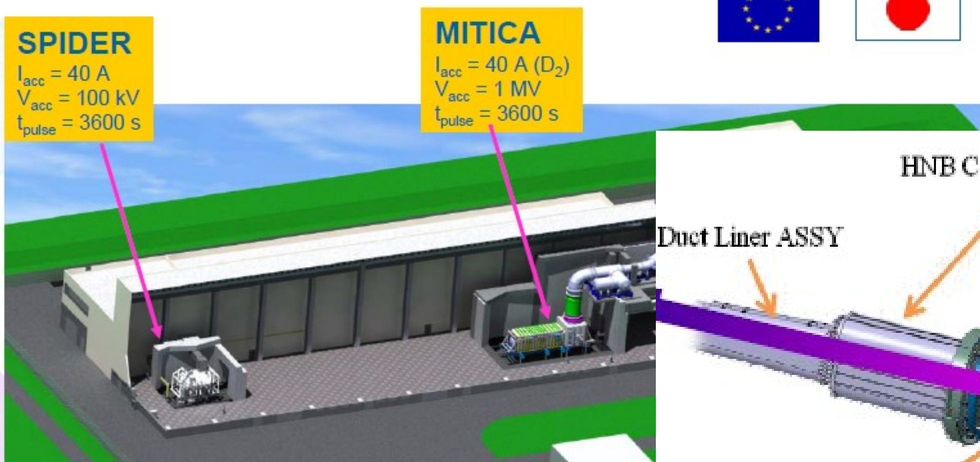
ITER Neutral Beam Test Facility (PRIMA)

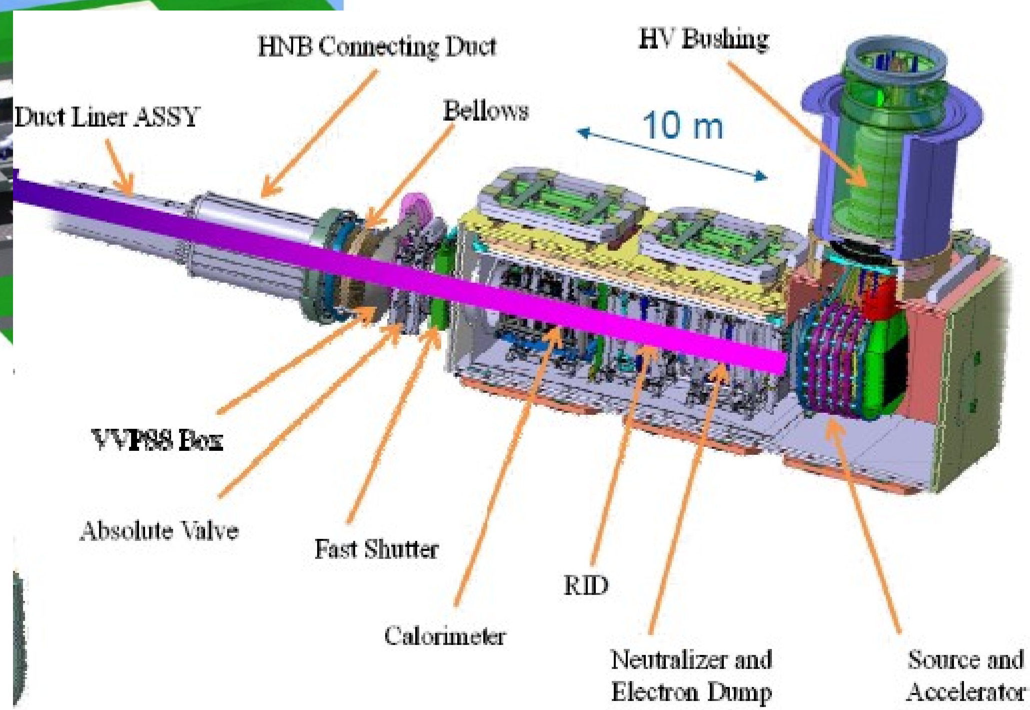
Fusion:
Plasma heating

Mission of PRIMA MITICA SPIDER :

- Optimise NBI operation
- Maximize reliability of injectors
- Develop technologies for injectors
- Test key remote handling tools and procedures
- Achieve nominal parameters:

A. Masiello et al., Fusion Eng. Des. **86** (2011) 860
P. Sonato et al., AIP Conf. Proc. **1515** (2013) 549
P. Sonato et al., Fusion Eng. Des. **84** (2009) 269





Energy

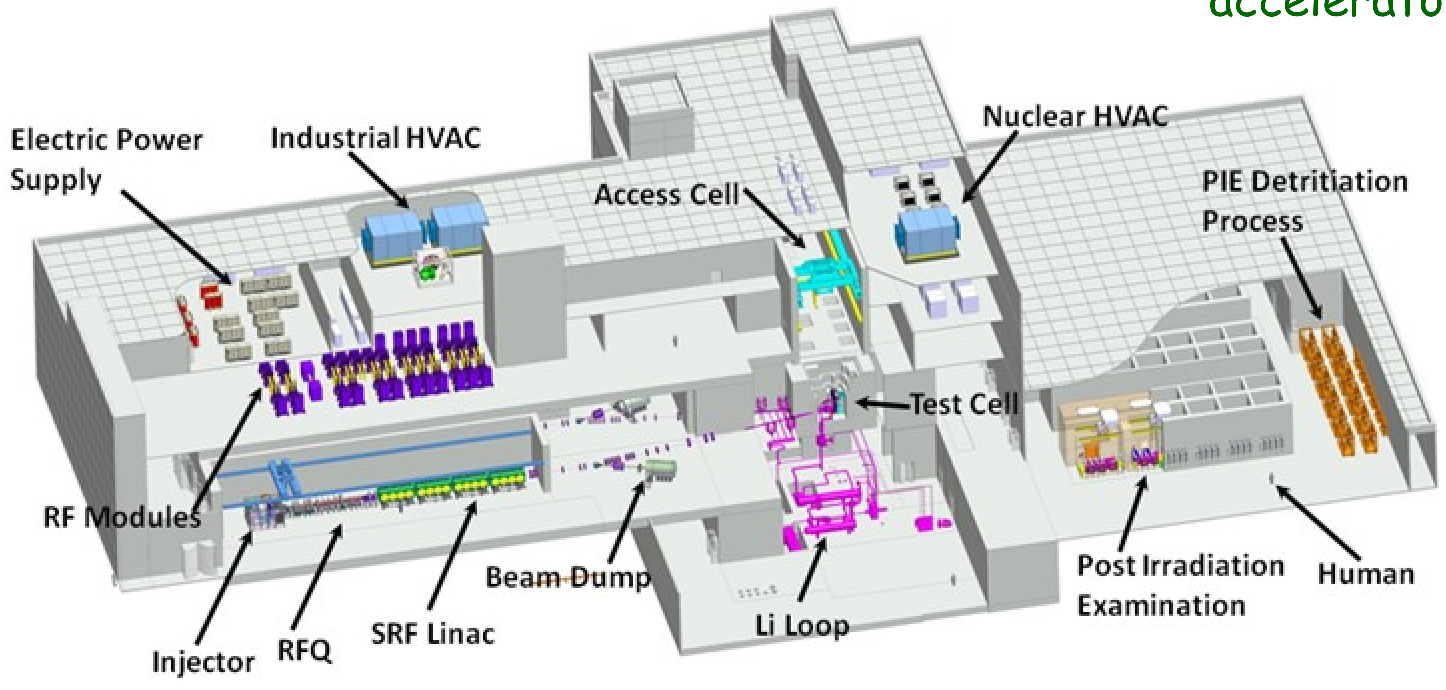
Fusion:
Materials research

DEMO: 10^{18} neutrons $m^{-2}s^{-1}$
at 14.1 MeV

IFMIF:

Create ~14 MeV neutrons
using Li(d,xn) reaction

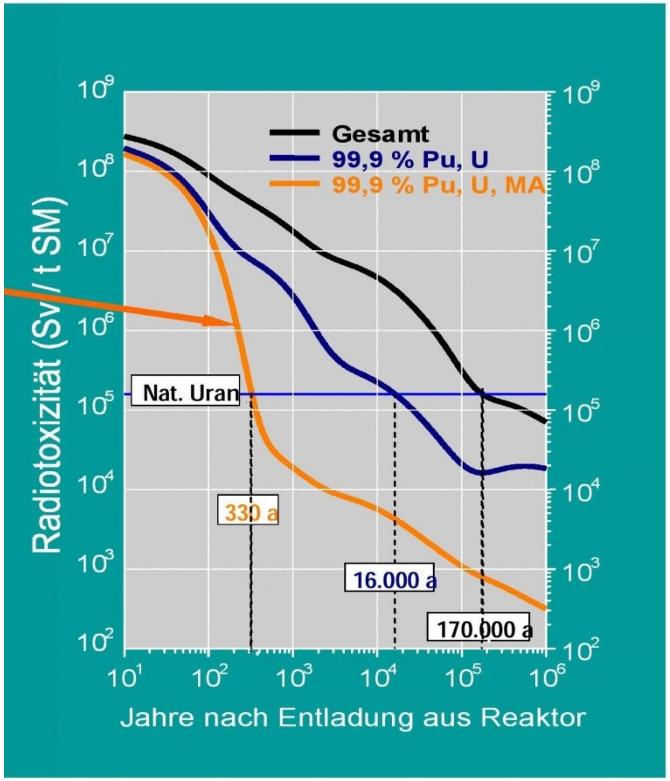
2 x 40 MeV, 125 mA linear
accelerators



Energy

Fission:
Accelerator Driven Systems

Significant problem: storage of radioactive waste
Main issue: minor actinides



Fast neutrons (> 1 MeV): fission of minor actinides

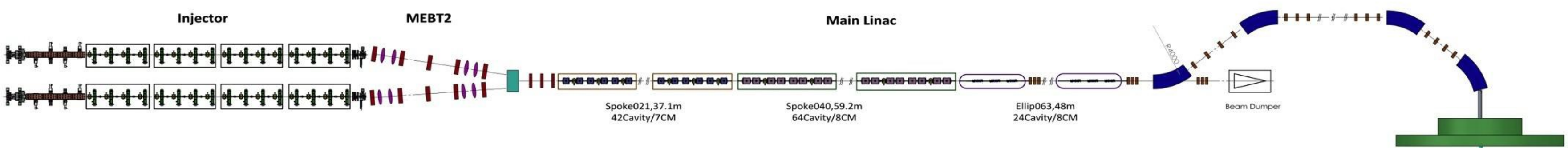
Need a source: accelerator
Several under study – Belgium, Japan, China

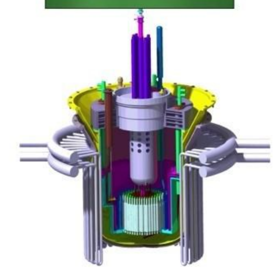
1.5 GeV protons at 10mA
15 MW

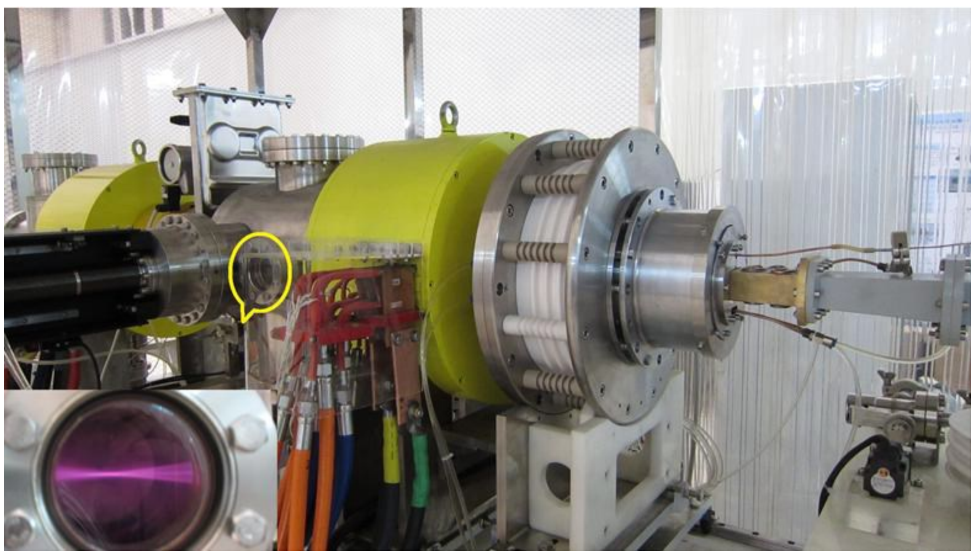
Energy

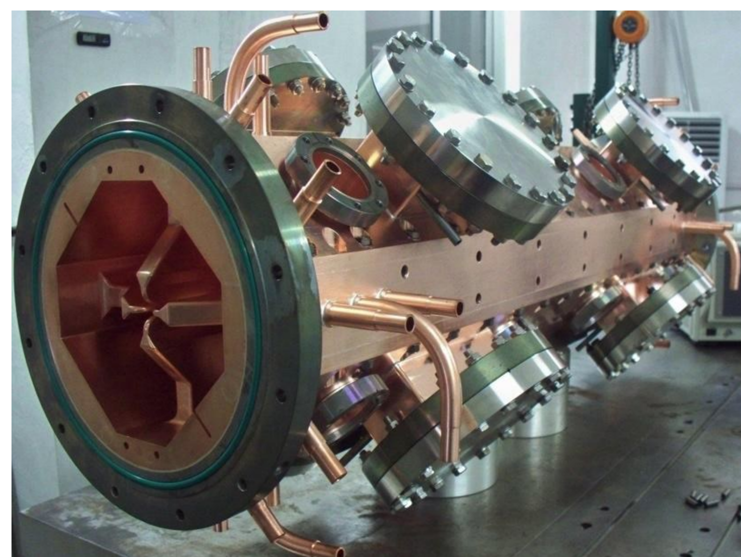
Fission:

Accelerator Driven Systems



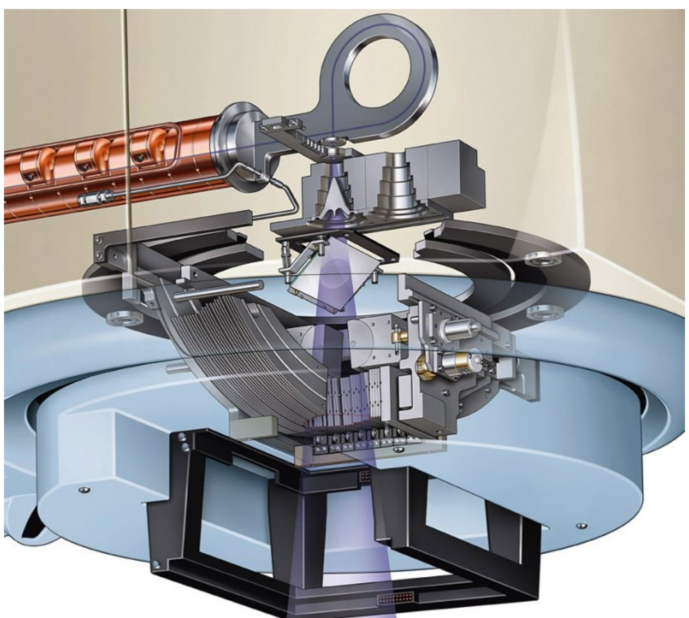






Medical Applications: Radiotherapy

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

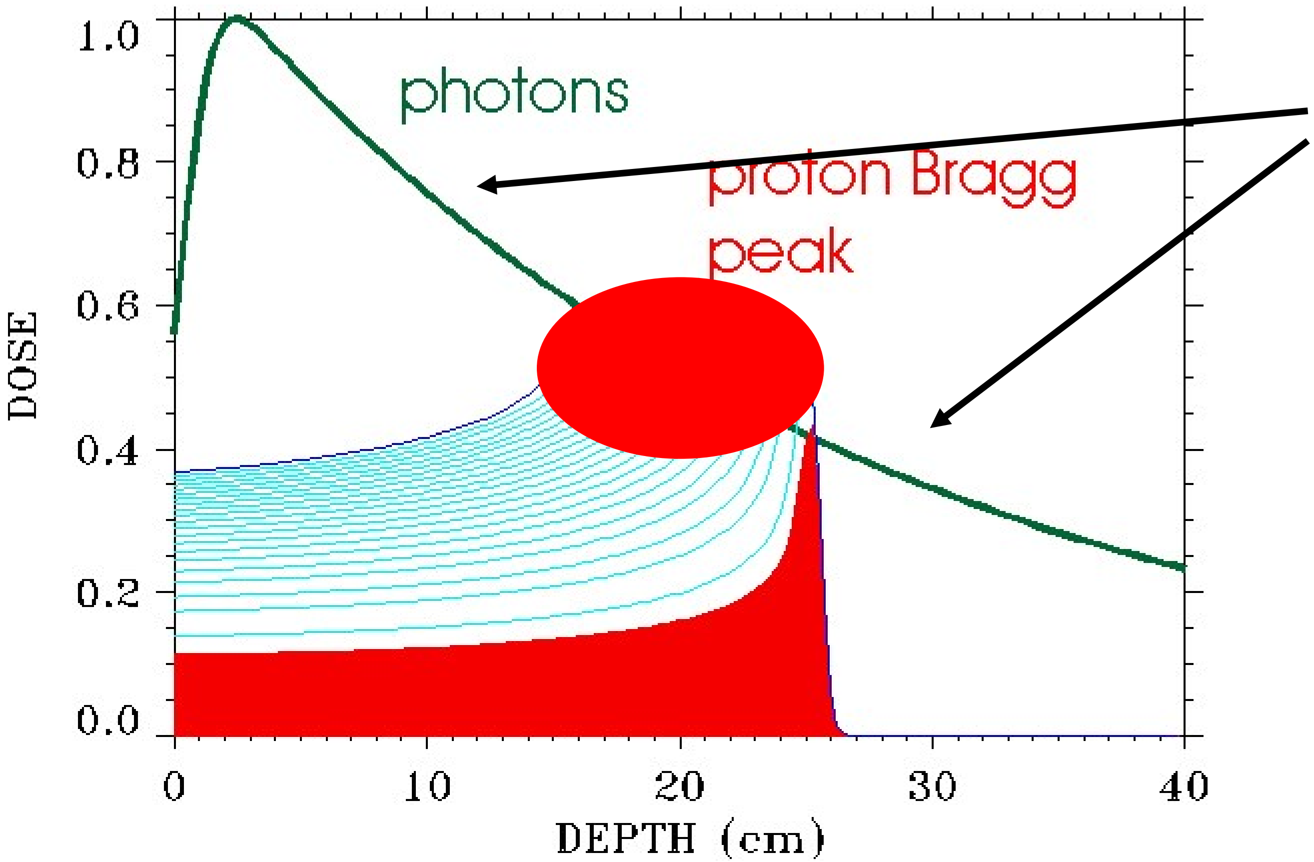


Beam Delivery

- Old technique: treat whole tumour in one go

- Newer technique: Intensity Modulated Radiotherapy

Dose Localisation



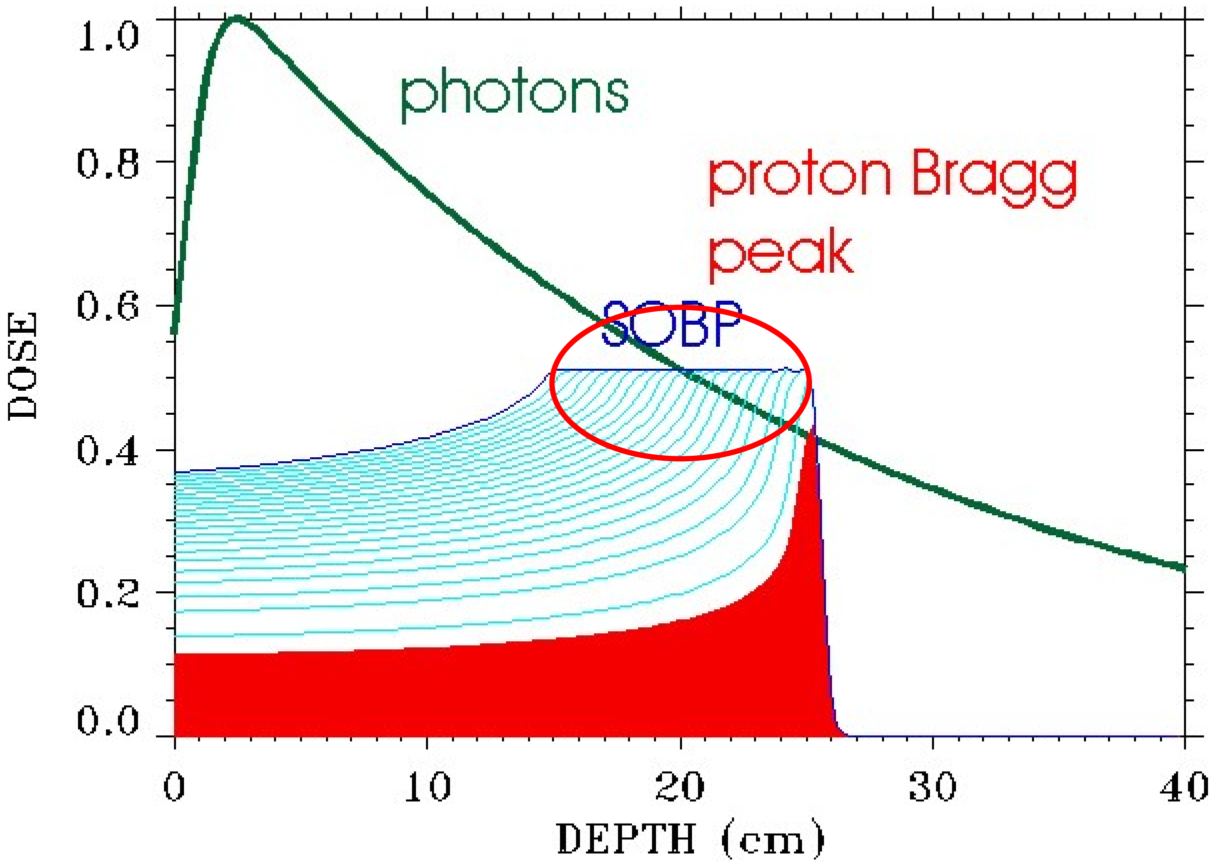
Damage to healthy tissue: side-effects!

But……… healthy cells have more repair mechanisms…

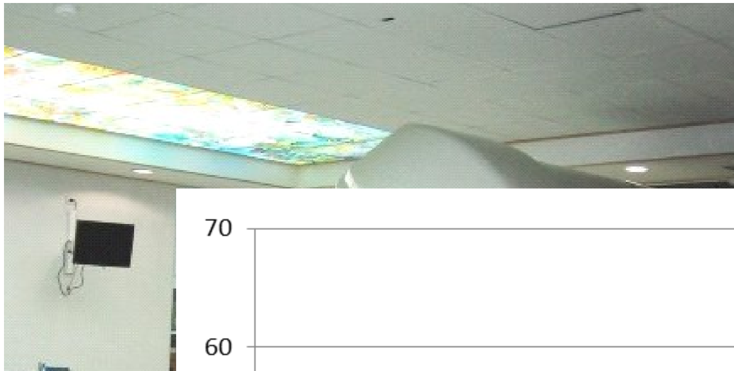
Fractions and IMRT

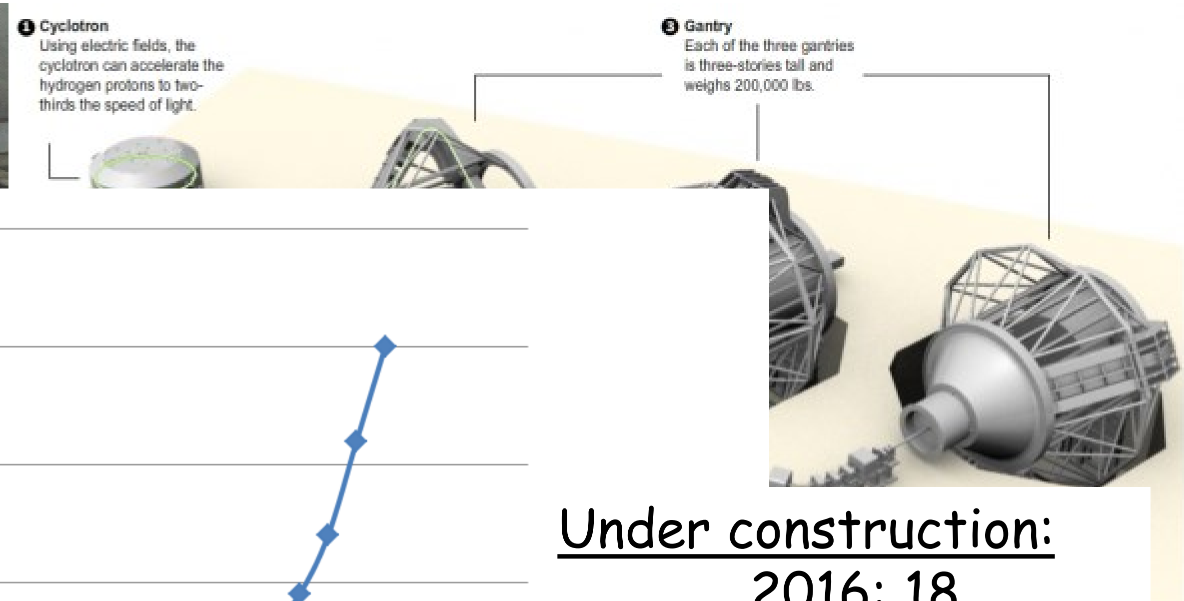
It's possible to do better!

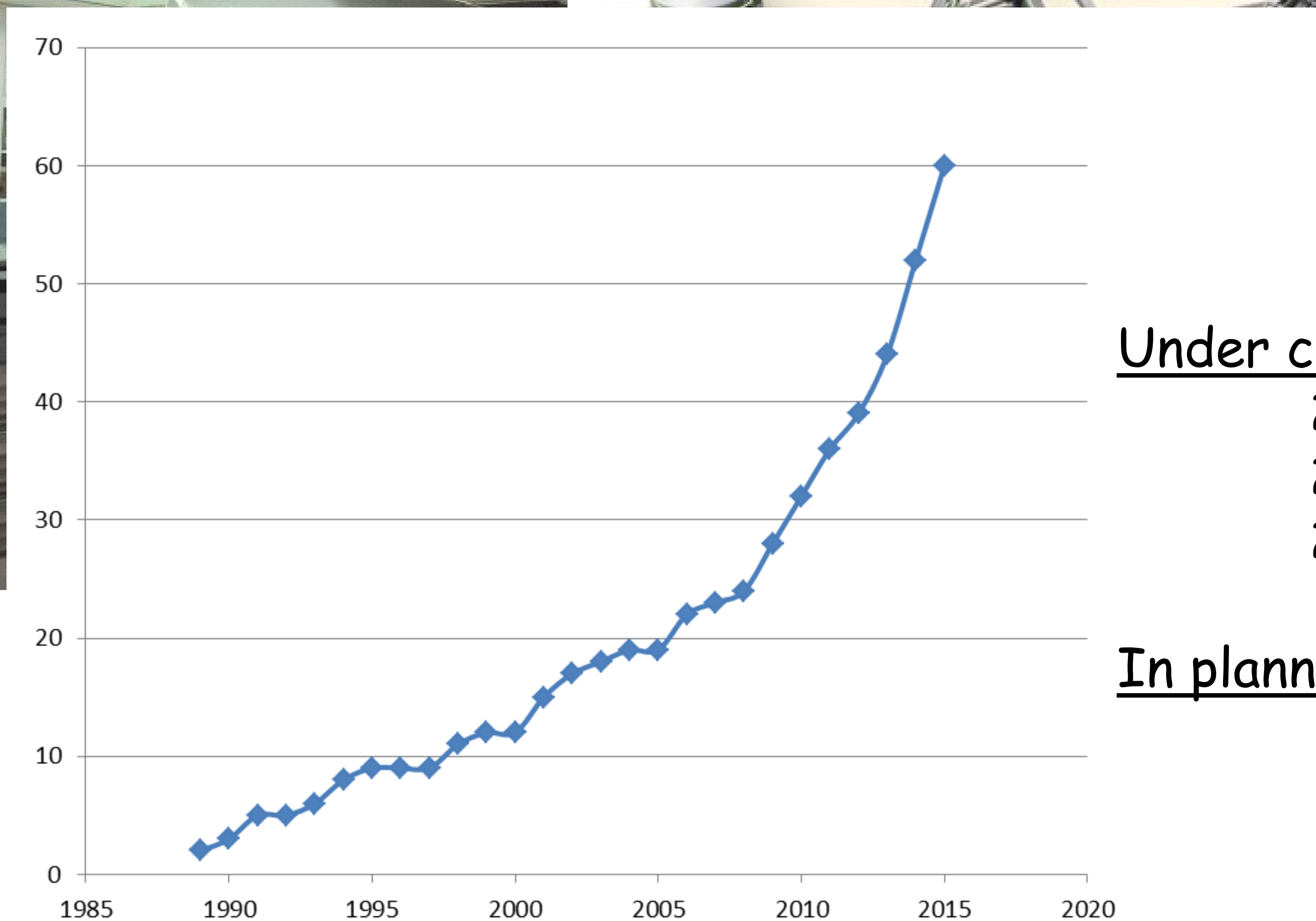
Dose Localisation



Proton Therapy







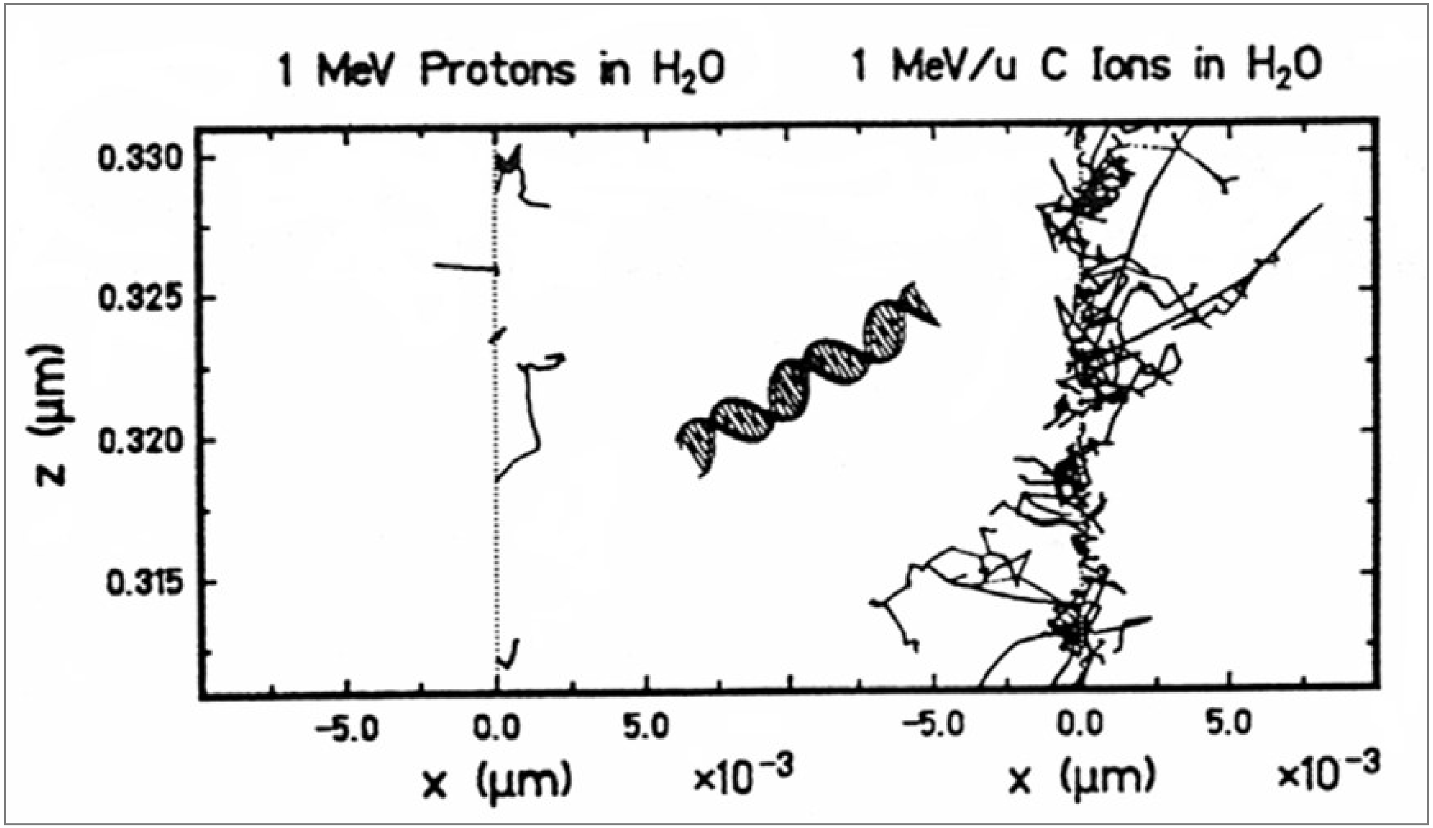
Under construction:

2016: 18
2017: 6
2018: 6

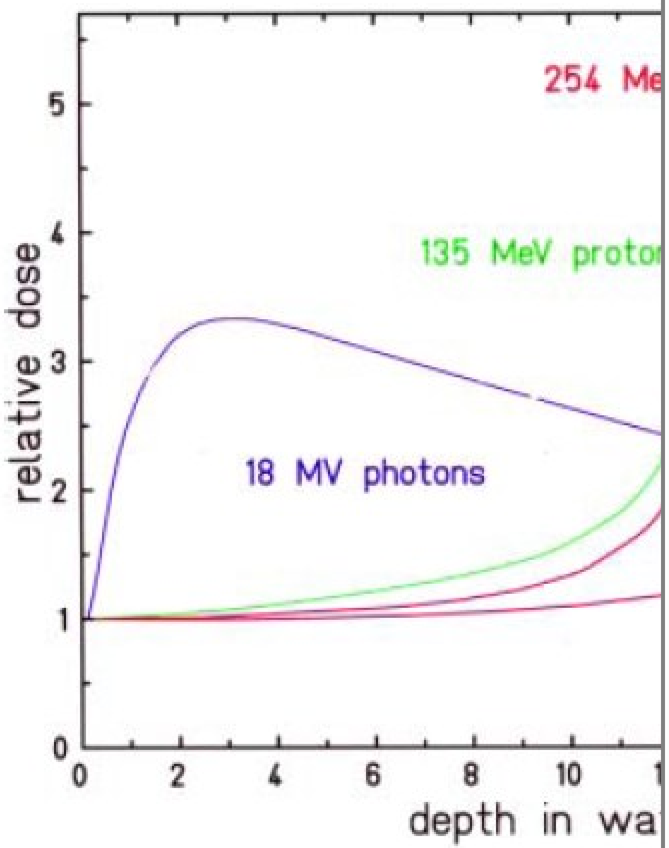
In planning:

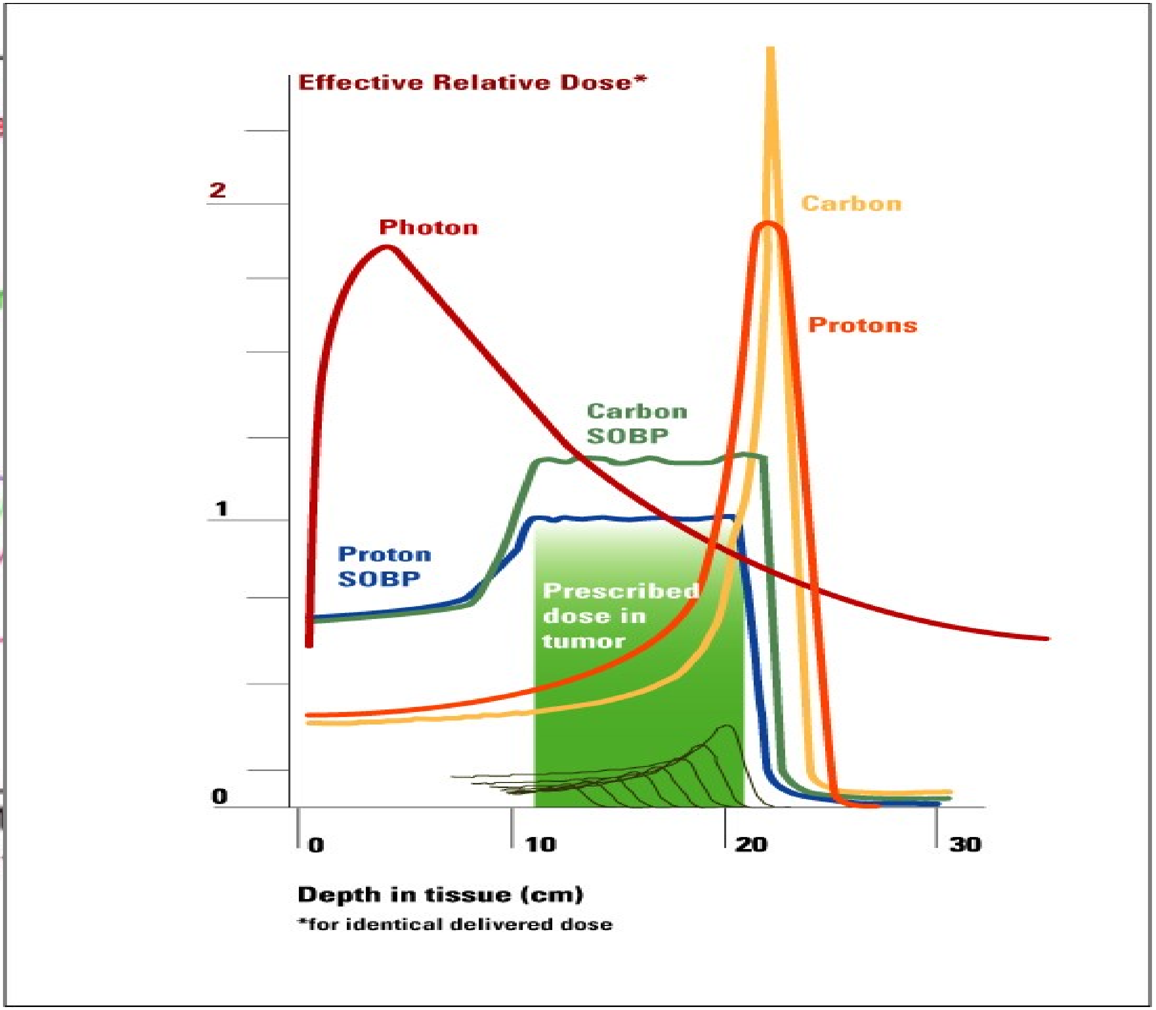
16

Dose Localisation

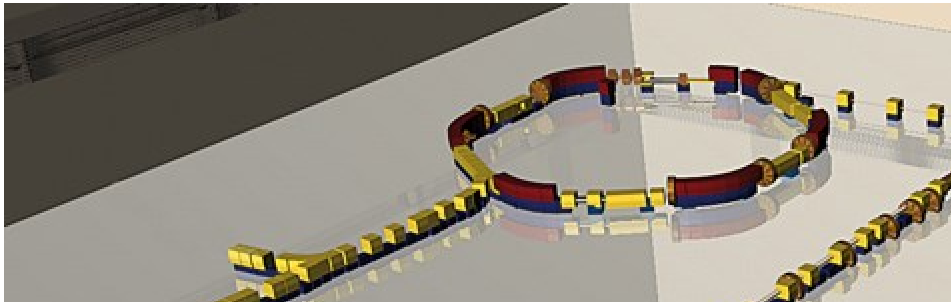


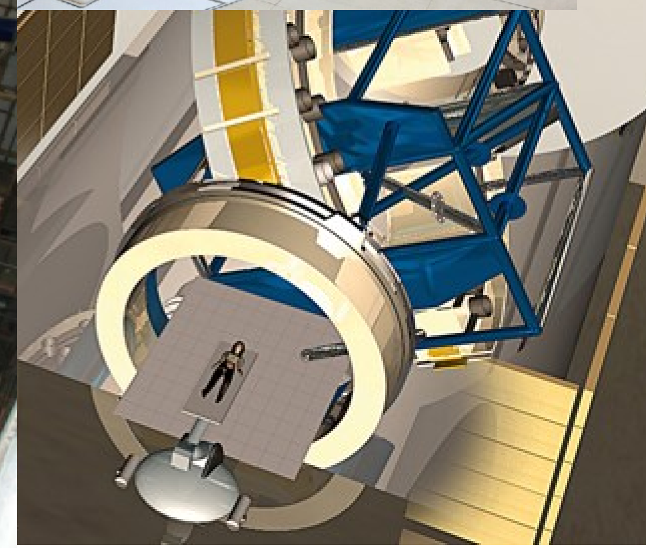
Dose Localisation





Charged Particle Therapy



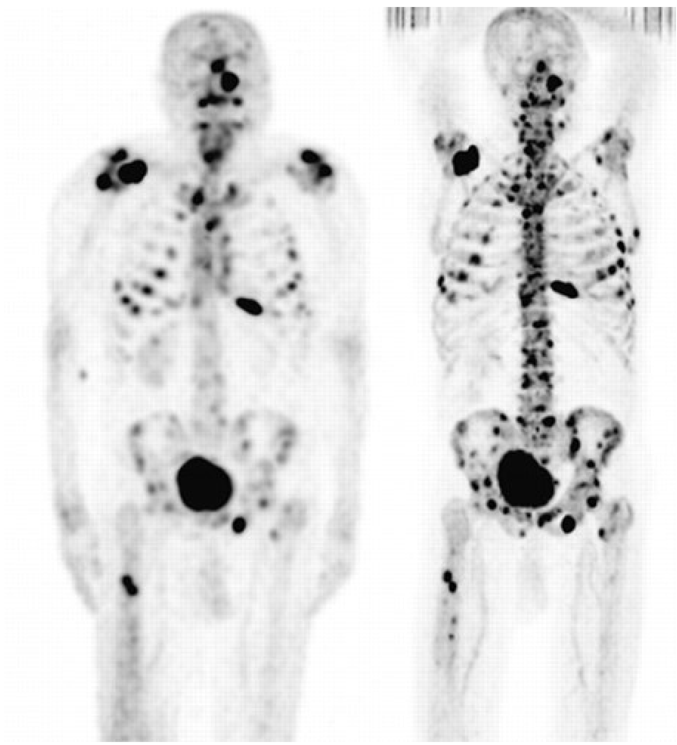


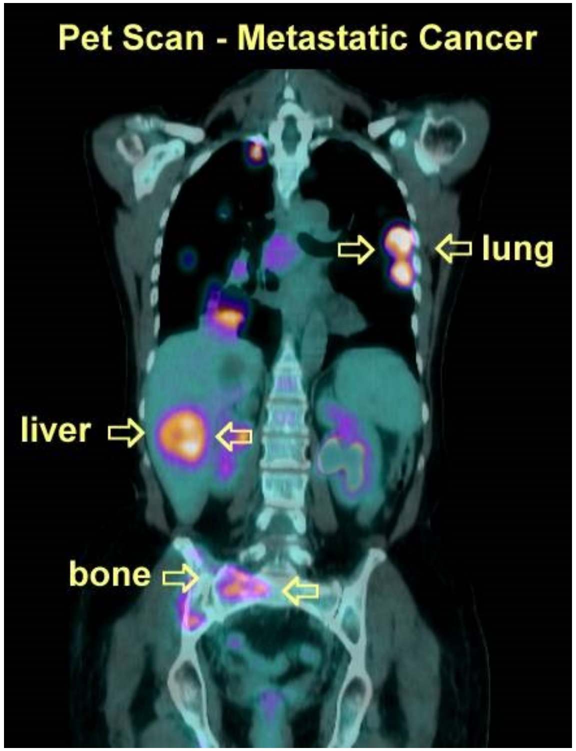
Carbon Therapy

- 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!

Medical: Radioisotope Production

- Imaging:
  - PET, mainly ^{18}F - accelerator produced
  - SPECT, mainly ^{99m}Tc (80%) – reactor produced
  - now usually combined with CT
- Therapy:
  - α or β emitters – mainly reactor produced





Medical: Radioisotope Production

- Accelerator isotope production – almost entirely cyclotrons

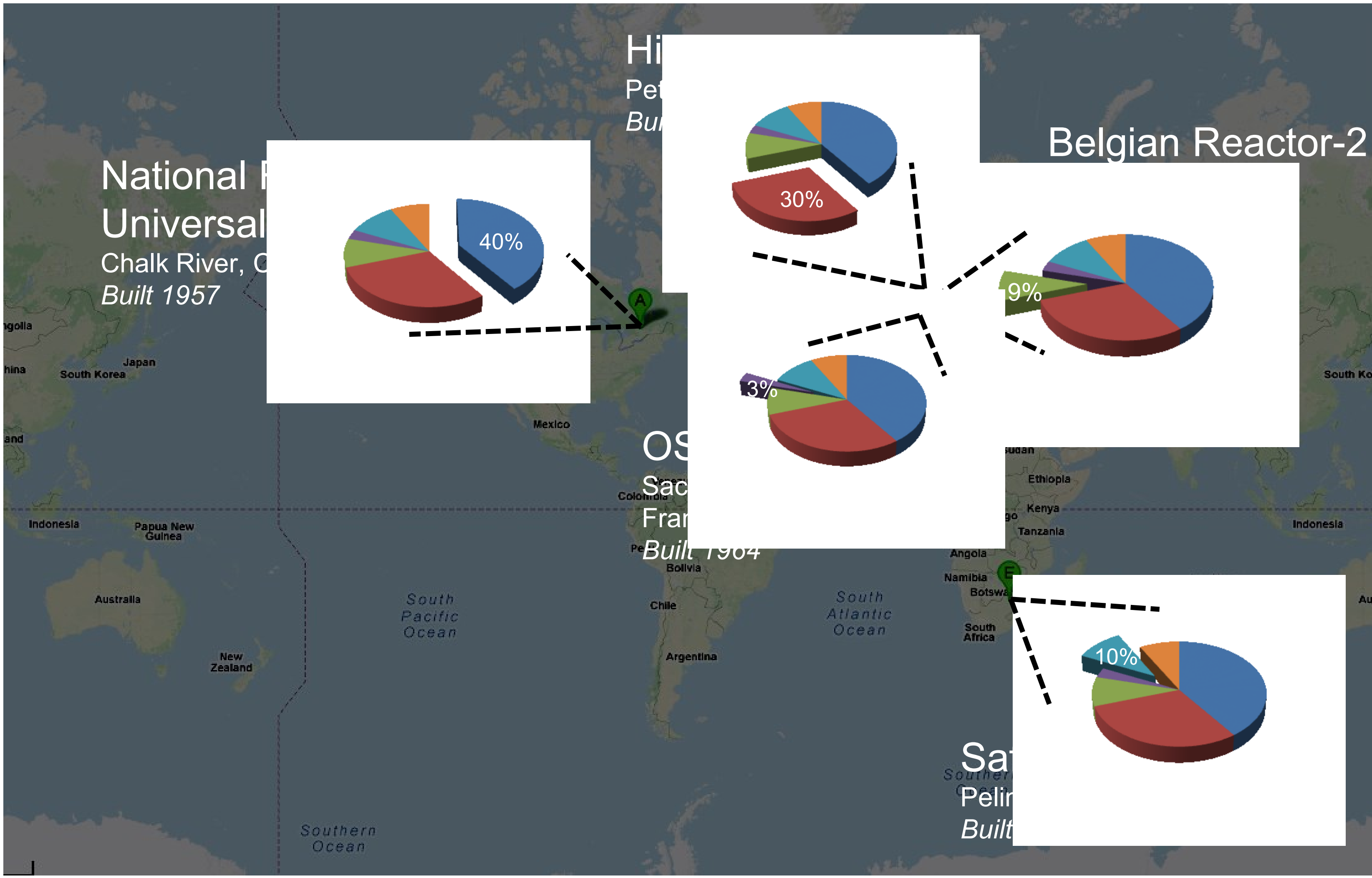
30 MeV, 1mA, IBA

14-19 MeV

11 MeV, Siemens

Radioisotope Issues

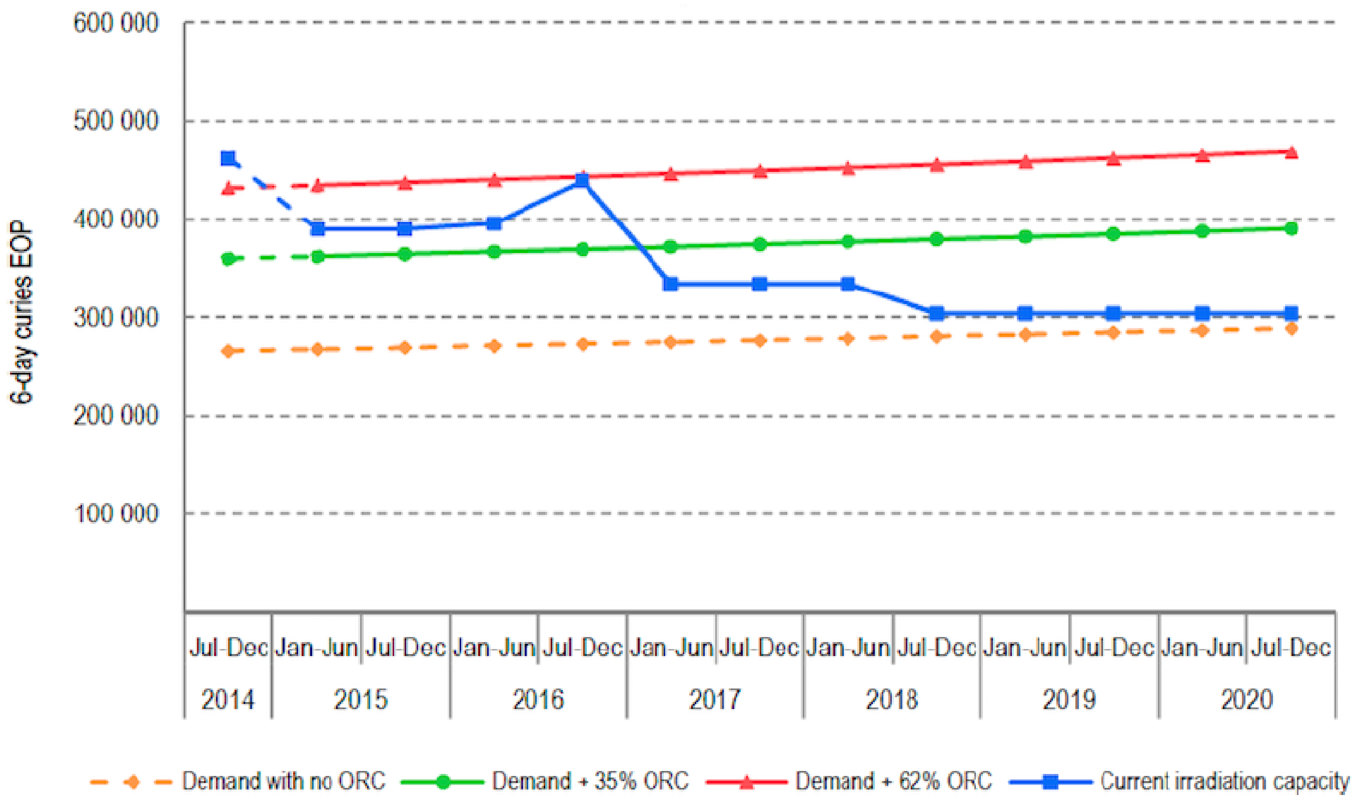
- ^{99m}Tc production



Google Maps

Radioisotope Issues

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



BNMS & STFC Report, December 2014

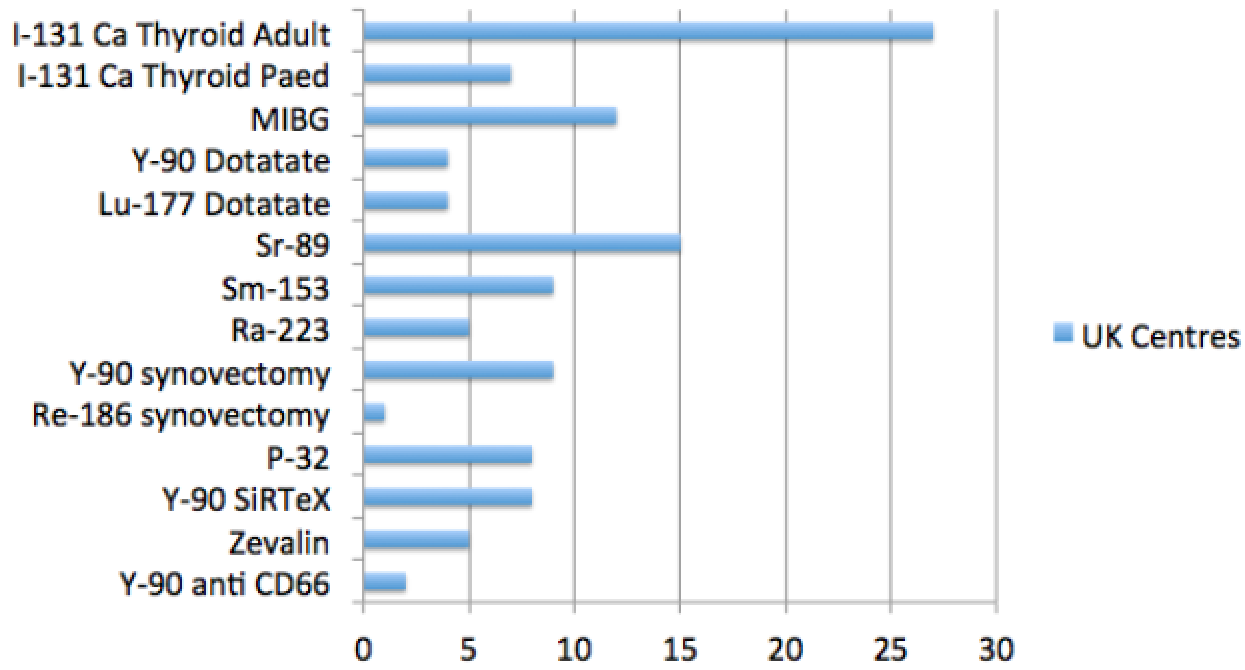
Various alternative production methods proposed, including accelerators

But none ideal

Radioisotope Issues

- All reactor produced
- None in the UK
- Supply can be a problem
- Some isotopes need a:
  ^{211}At, ^{67}Cu, ^{47}Sc

Therapeutic radioisotopes



Roles of FFAGs

Fixed Field Alternating Gradient accelerator

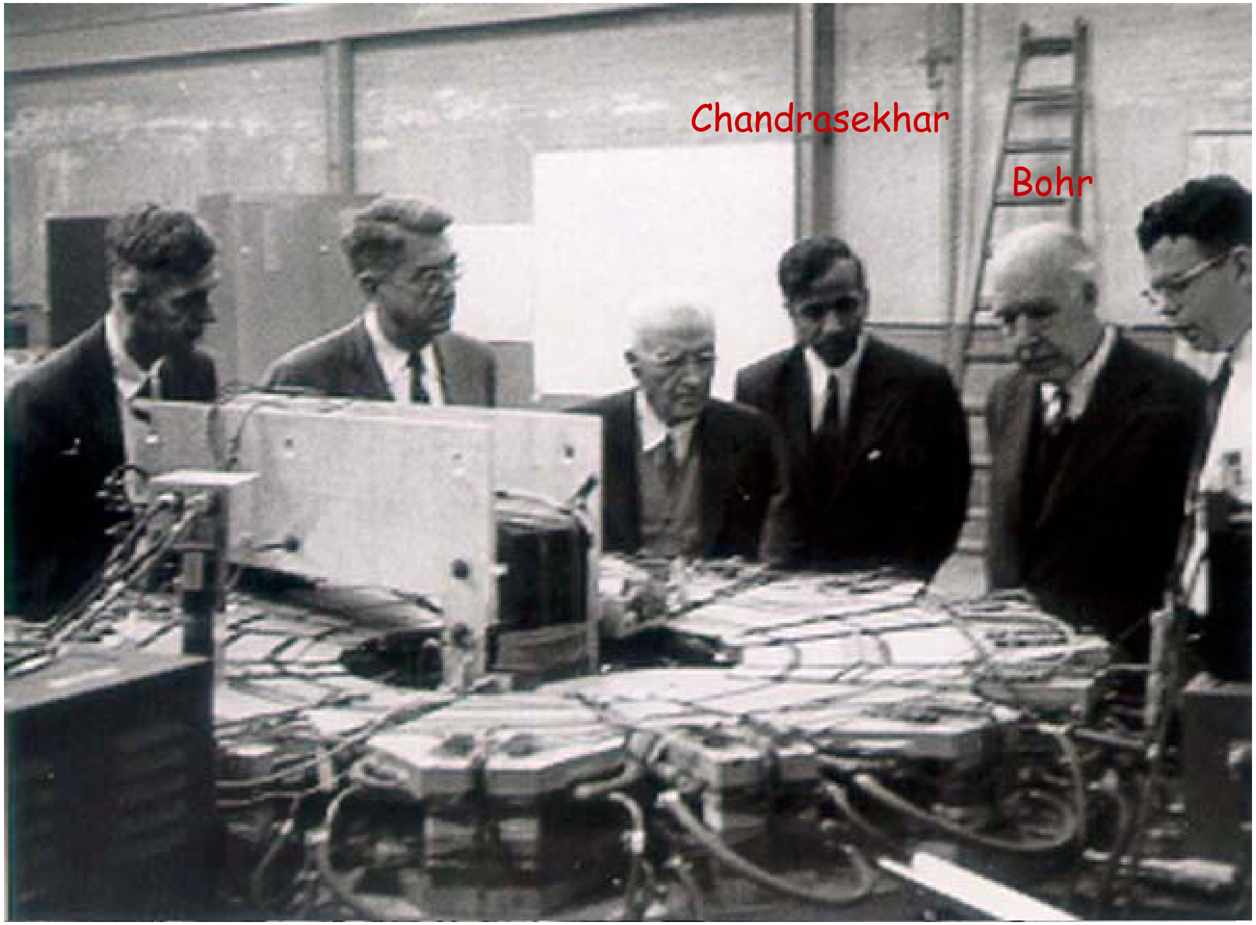
Synchrotron-like

Cyclotron-like

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

A Brief History of FFAGs

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

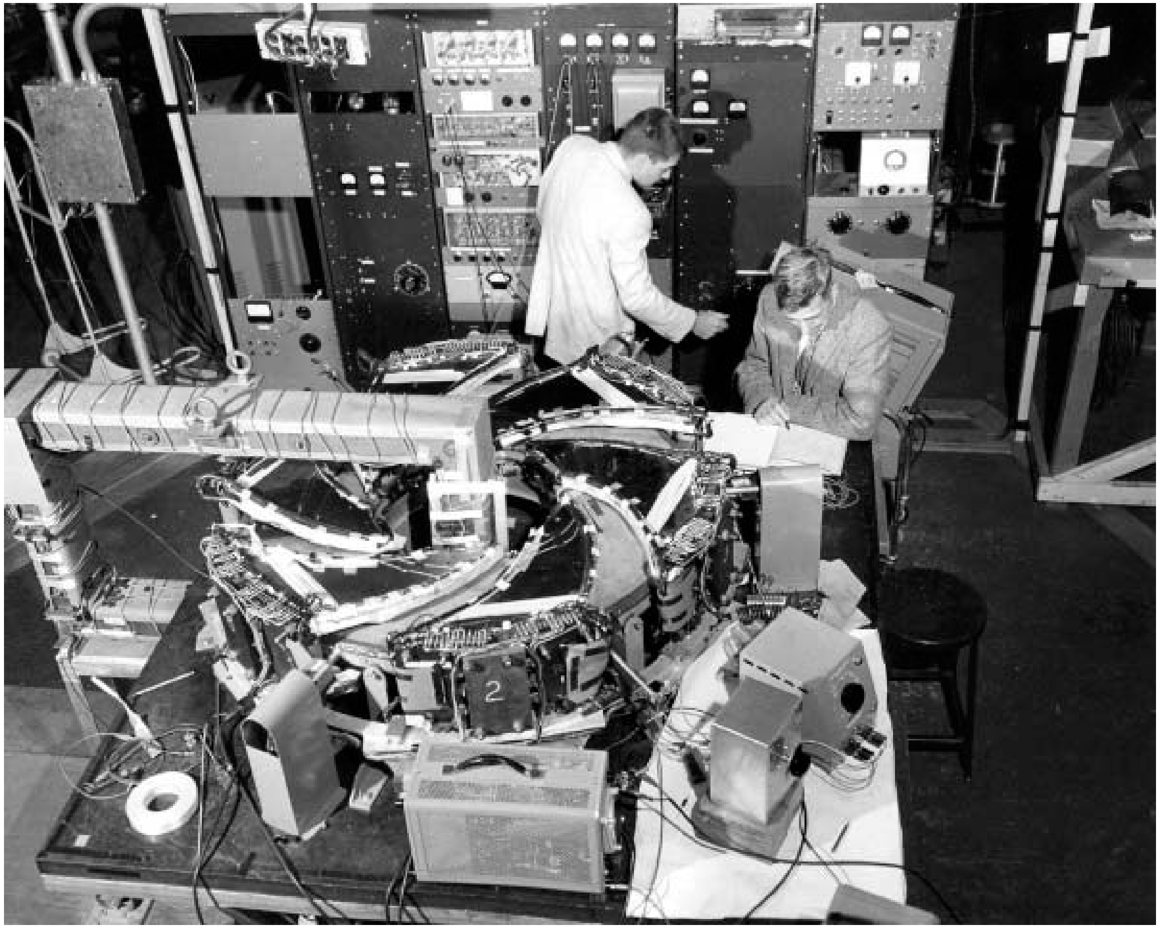


20 to 400 keV machine

Operated at MURA in 1956

A Brief History of FFAGs

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

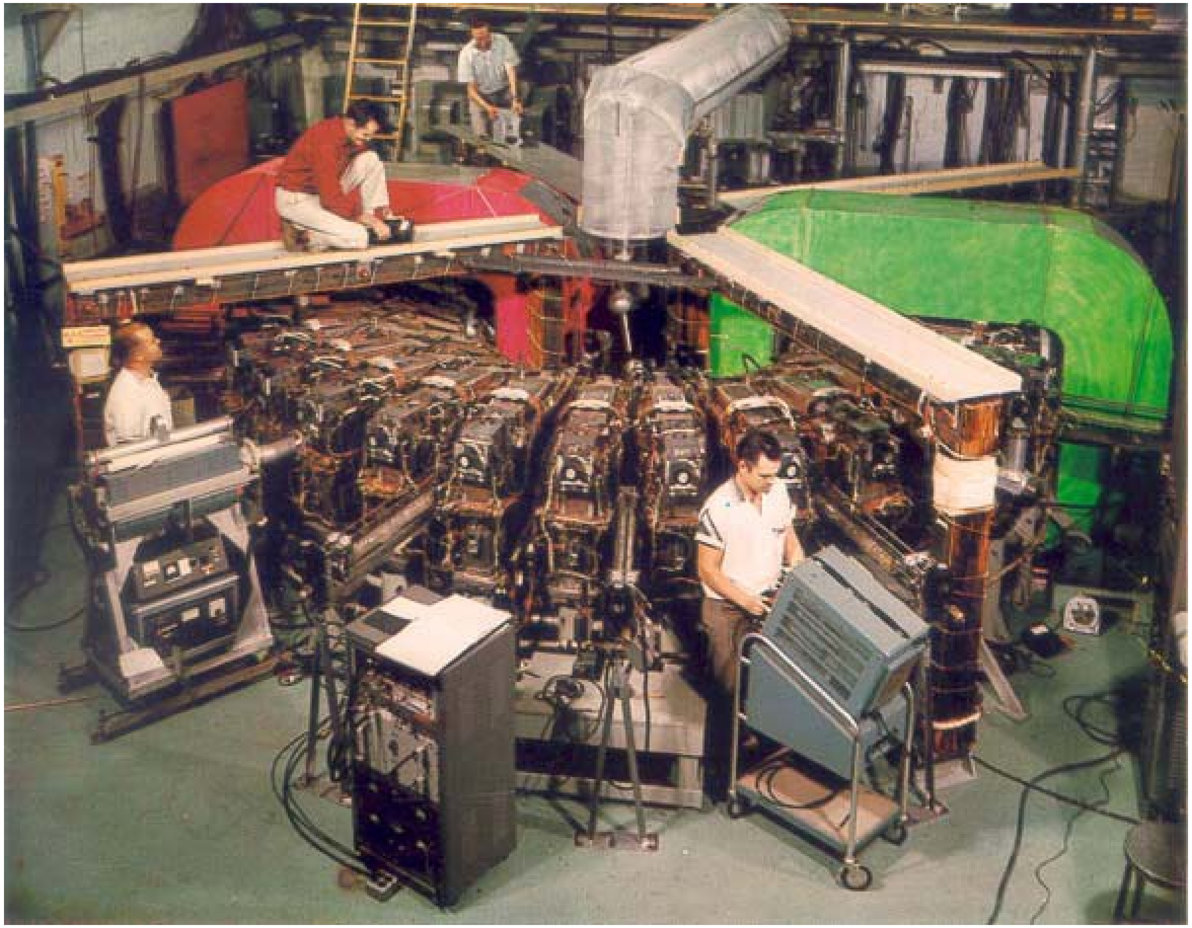


Spiral sector machine

Operated at MURA in 1957

A Brief History of FFAGs

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

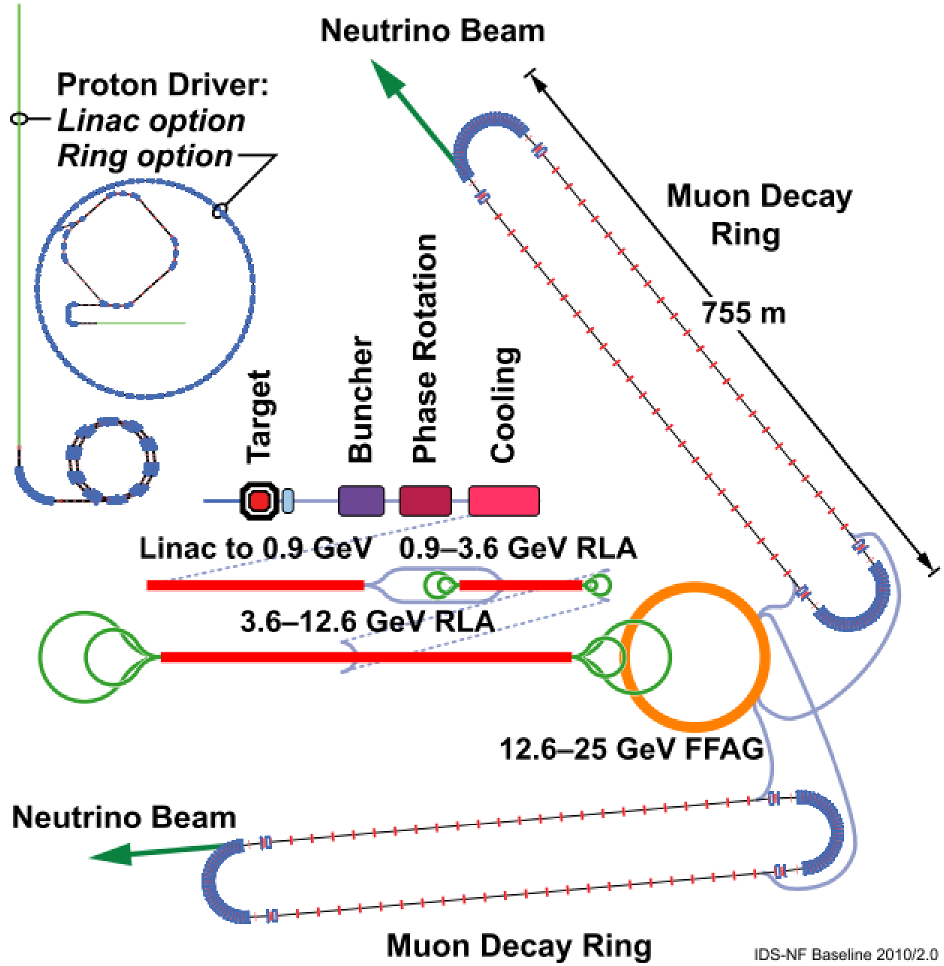


100keV to 50MeV machine

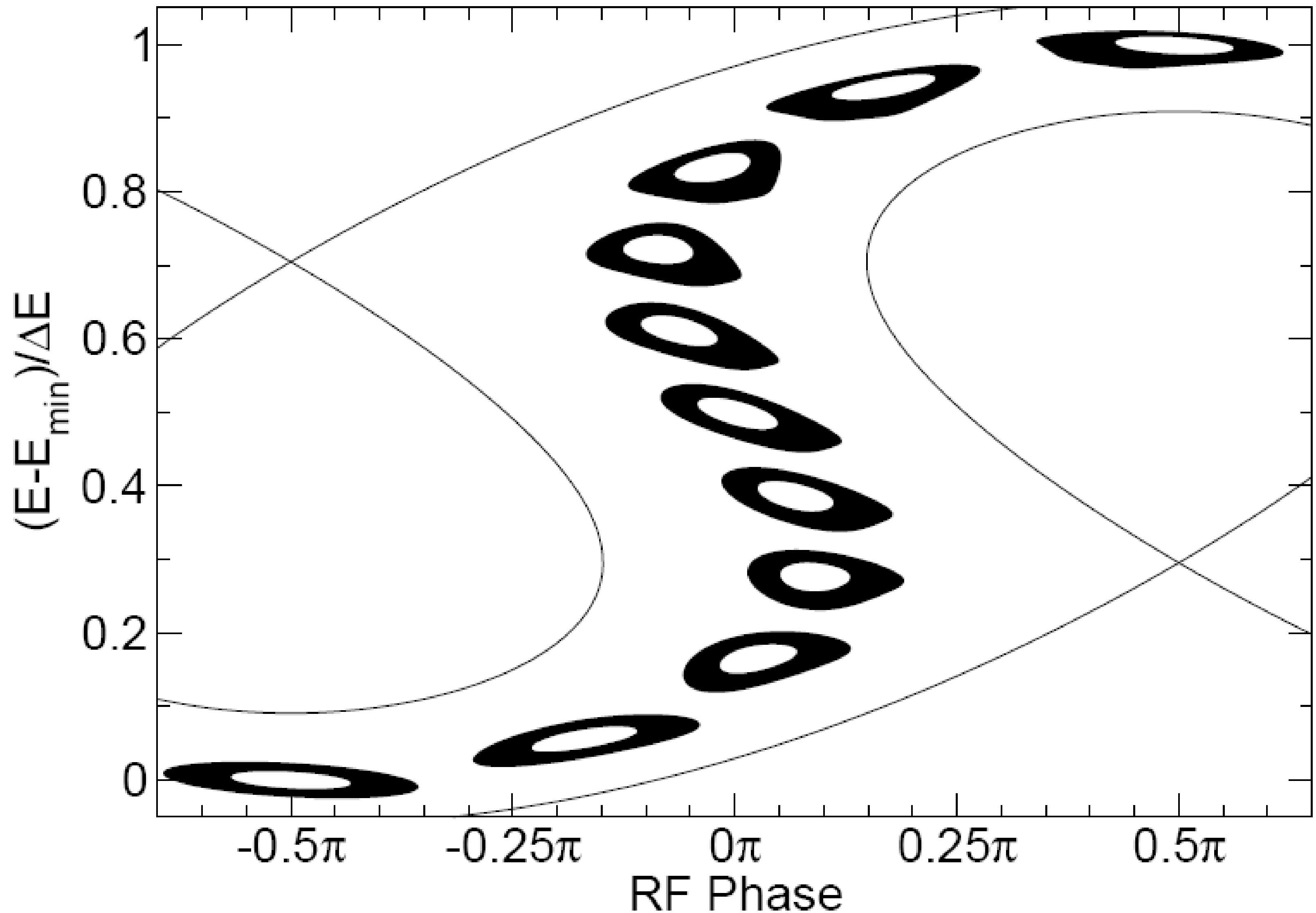
Operated at MURA in 1961

(Non-scaling) FFAG Development

- Originally invented for:
  - fast acceleration
  - large DA



(Non-scaling) FFAG Development



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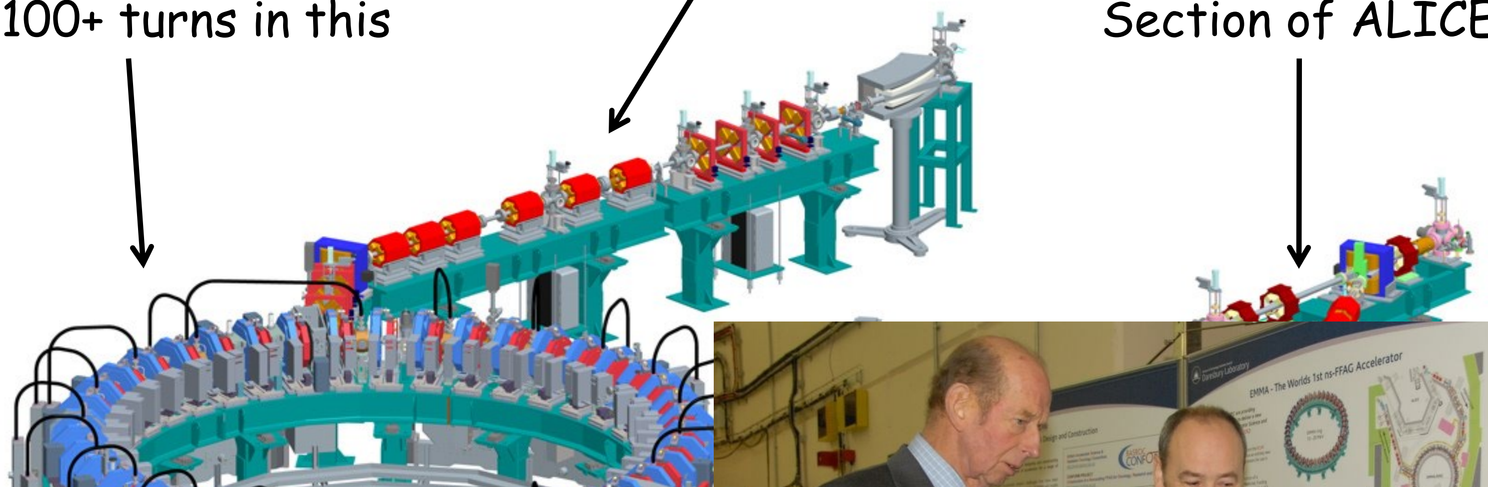
EMMA

Diagnostics beam line

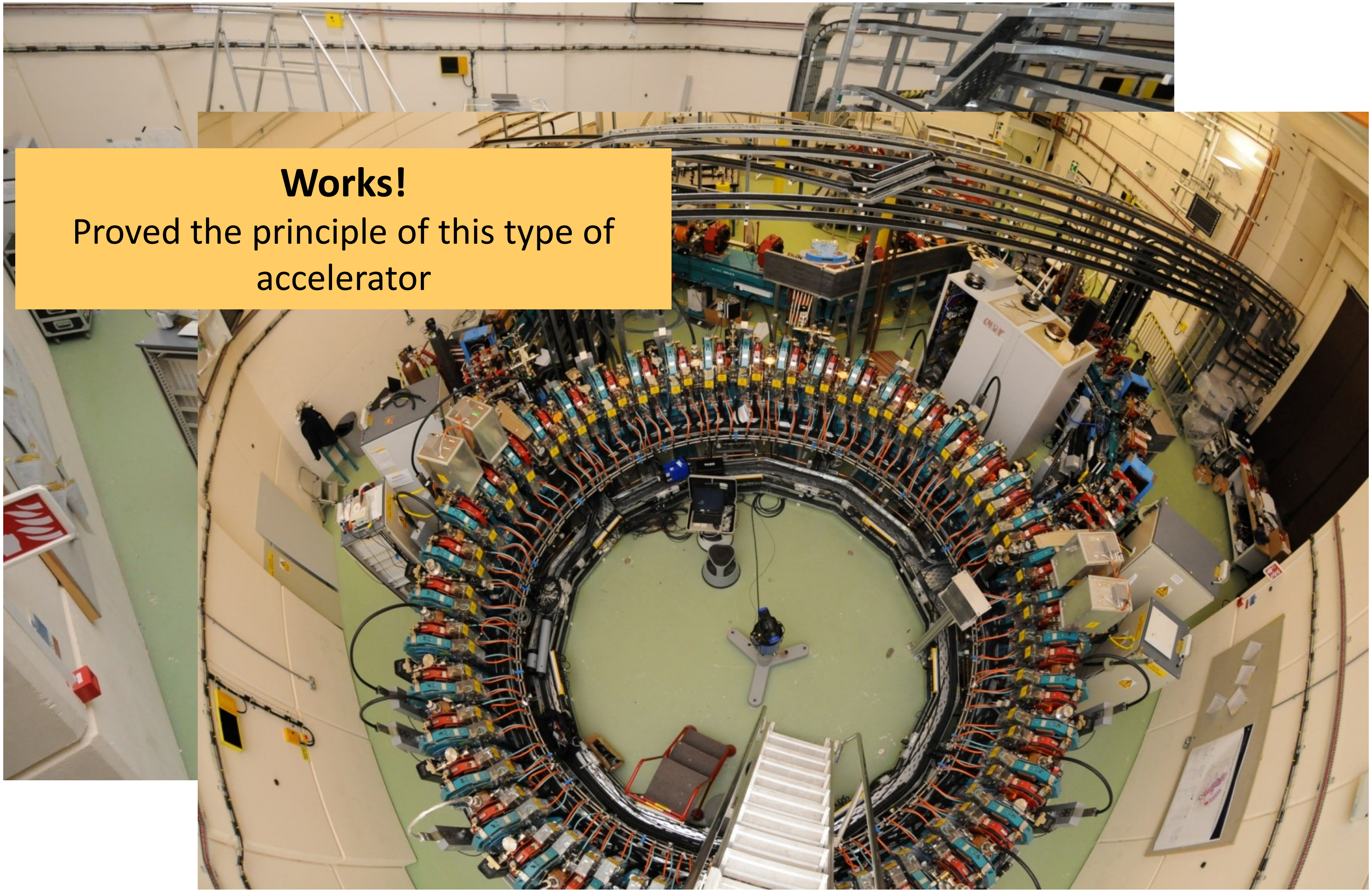
EMMA ring: beam makes 5 to 100+ turns in this

Section of ALICE



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

EMMA



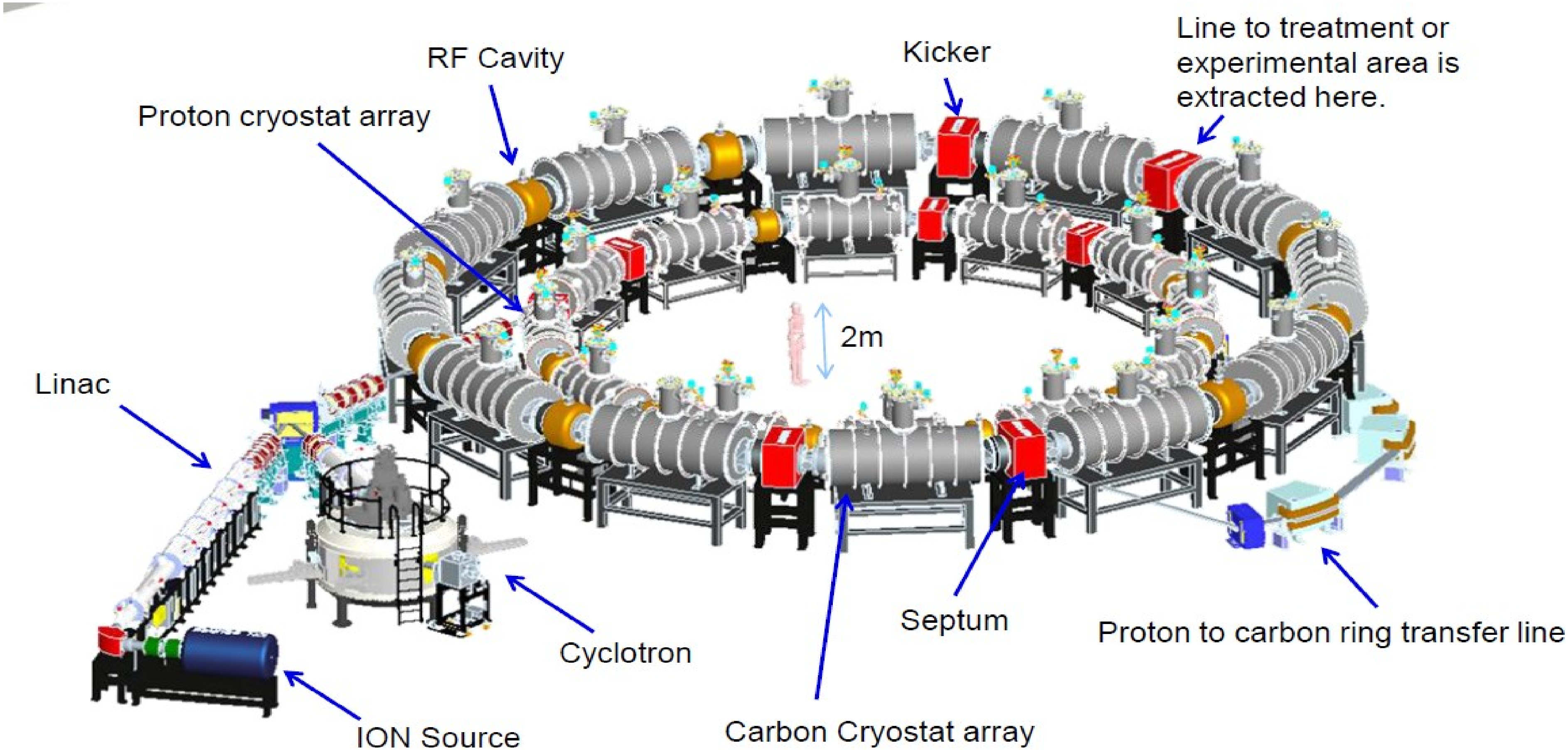
Works!

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



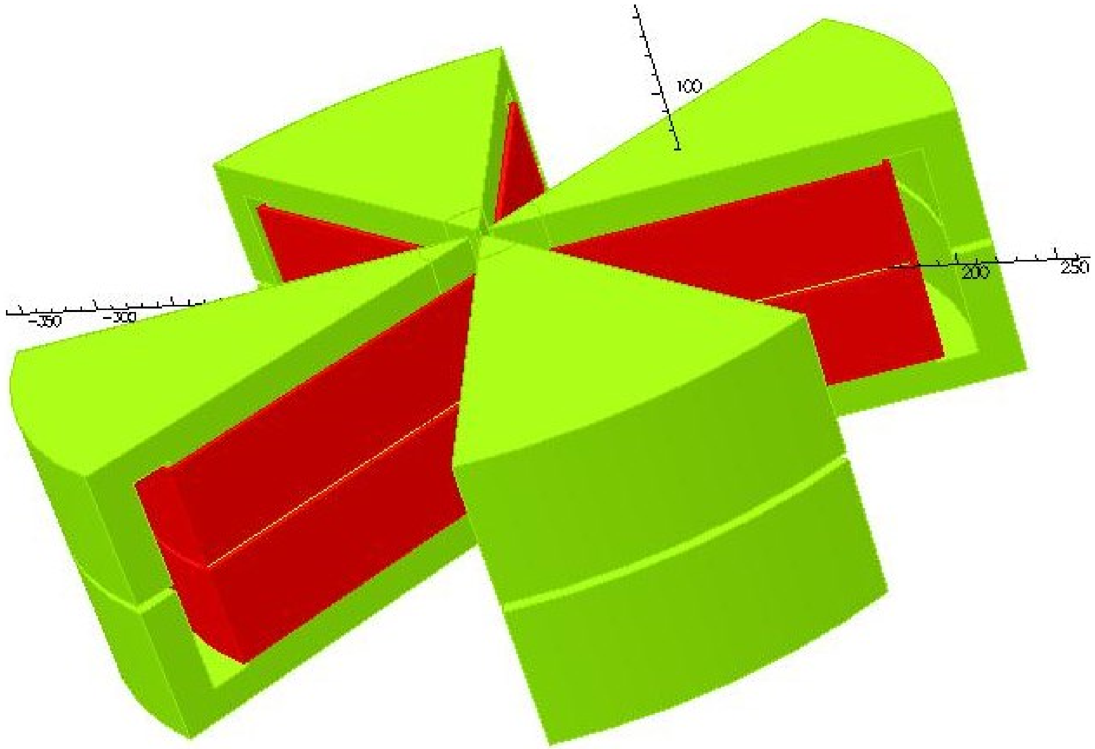
RF Cavity
Kicker
Line to treatment or experimental area is extracted here.
Proton cryostat array
2m
Linac
Cyclotron
Septum
Proton to carbon ring transfer line
ION Source
Carbon Cryostat array

More recent developments

- Small UK-US collaboration: new FFAG design
- More cyclotron-like
  - fixed RF frequency
  - very high beam currents
- Radioisotope production
- Ion beam therapy

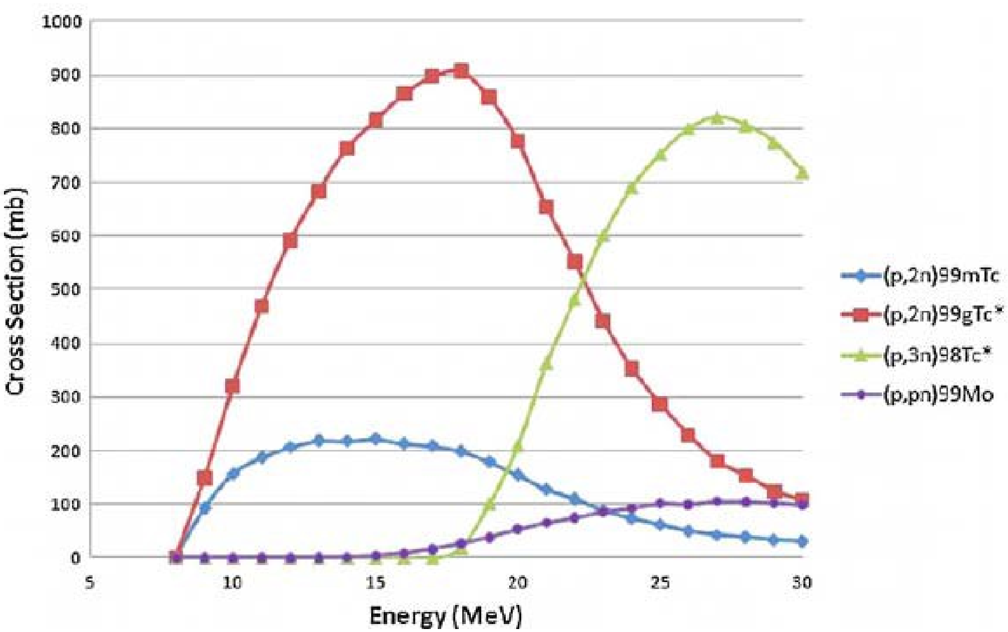
Wedge-shaped magnets
Three forms of focussing:
- gradient: up to r^2
- edge
- weak

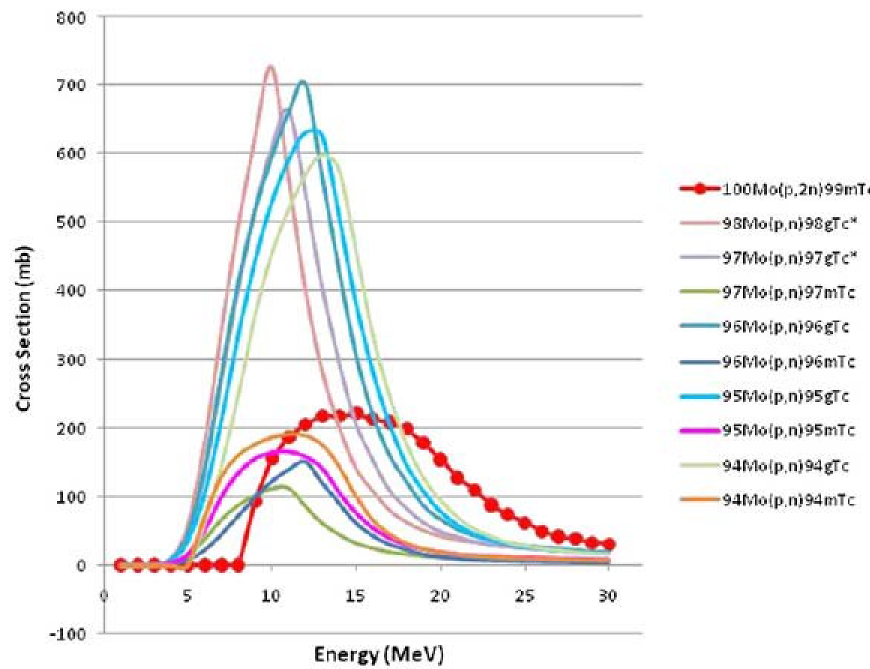
Allows simultaneous time of flight and focussing control



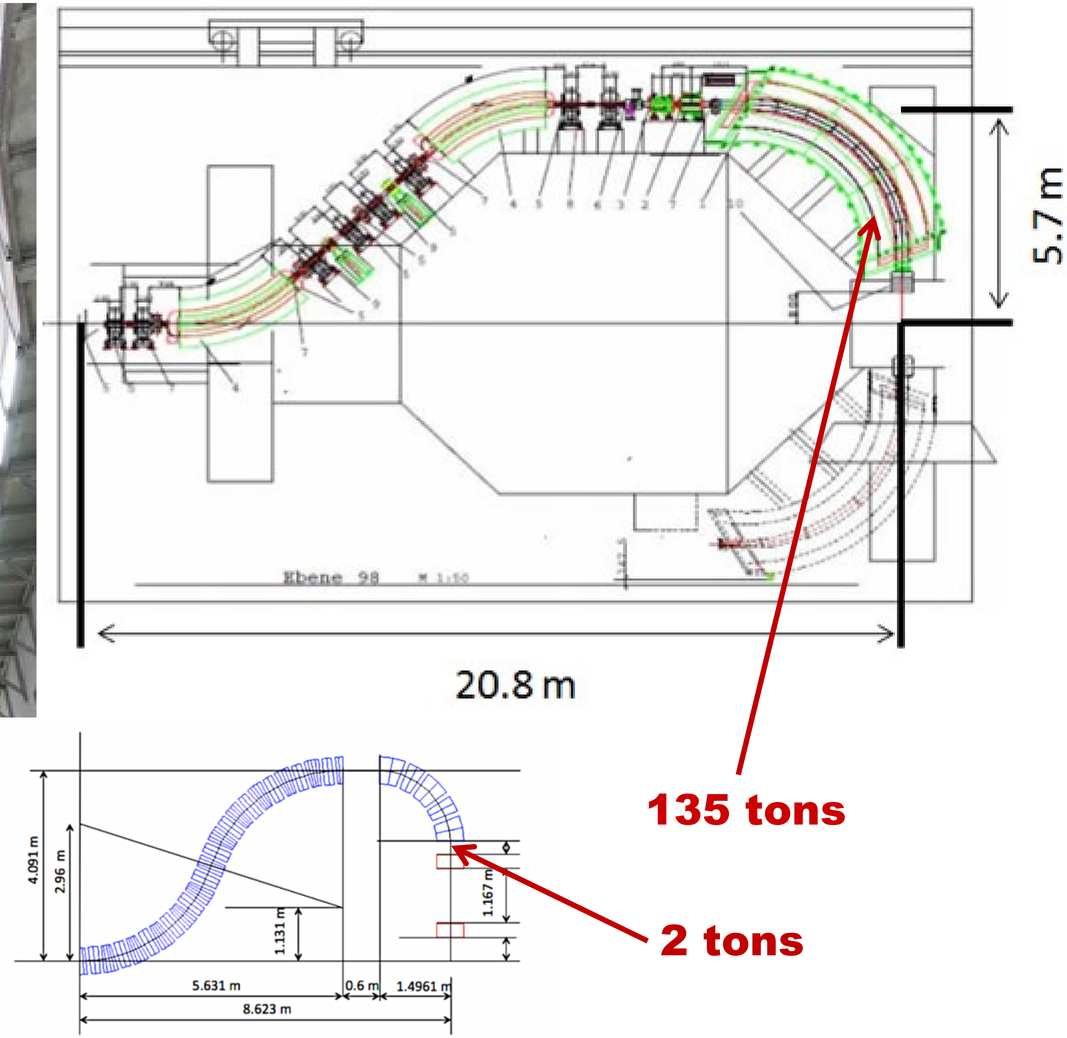
Radioisotope Production

- PIP:
  - 75 keV to 28 MeV
  - 20 mA demonstrated (in software!)
  - ^{99m}Tc and therapeutic radioisotopes
  - injection scheme done
  - initial magnet design done
  - internal target looks feasible





Carbon therapy



Helium Therapy

- Already size reduction looks possible for carbon
- Main emphasis: helium
  - about half way between protons and carbon
  - but better than C in two respects, esp 900 vs 4800 MeV
  - also possible to do imaging with deuterons
  - collaboration forming to do radiobiology
- Initial design, two rings:
  - expanded PIP from 0.5 MeV to 360 MeV
  - bigger ring with longer straight sections to 900 MeV
- Now looks possible to do the whole lot with an expanded PIP
  - still isochronous
  - still with tune control
- Main problem: getting funding to develop either machine!

Conclusions

- Accelerators are important for many everyday applications
- This is rather poorly known, even amongst people who use them!
- Various attempts to address this:
  - Accelerators for America's Future
  - Accelerators for Society
  - Applications of Particle Accelerators in Europe
- Developing a "new" type of accelerator for medical applications
- Plus, there's the day job……..

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European Spallation Source