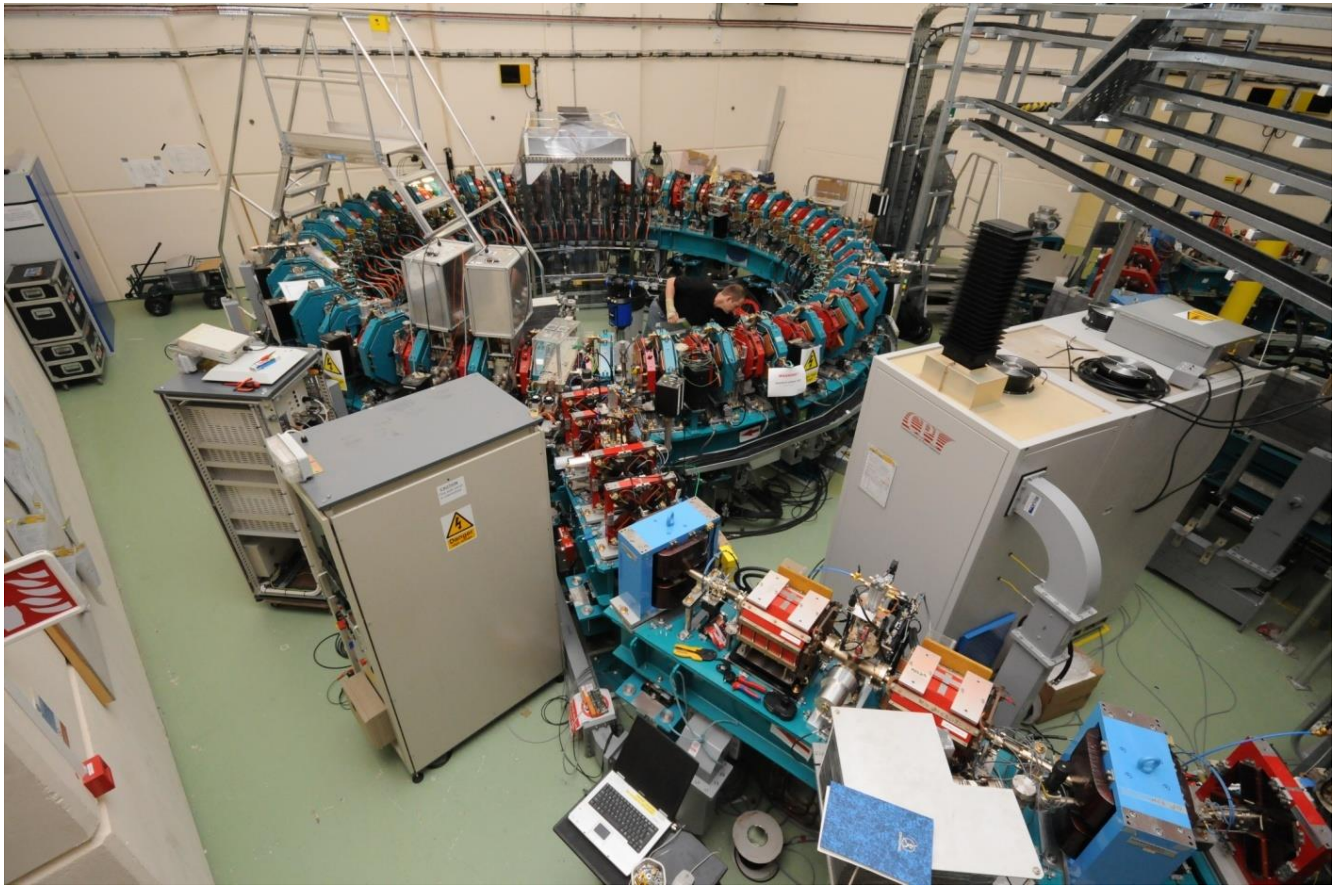
Applications of Accelerators

Prof Rob Edgecock
Rutherford Appleton Laboratory and
University of Huddersfield



Outline

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

- Medical applications:
  - cancer therapy

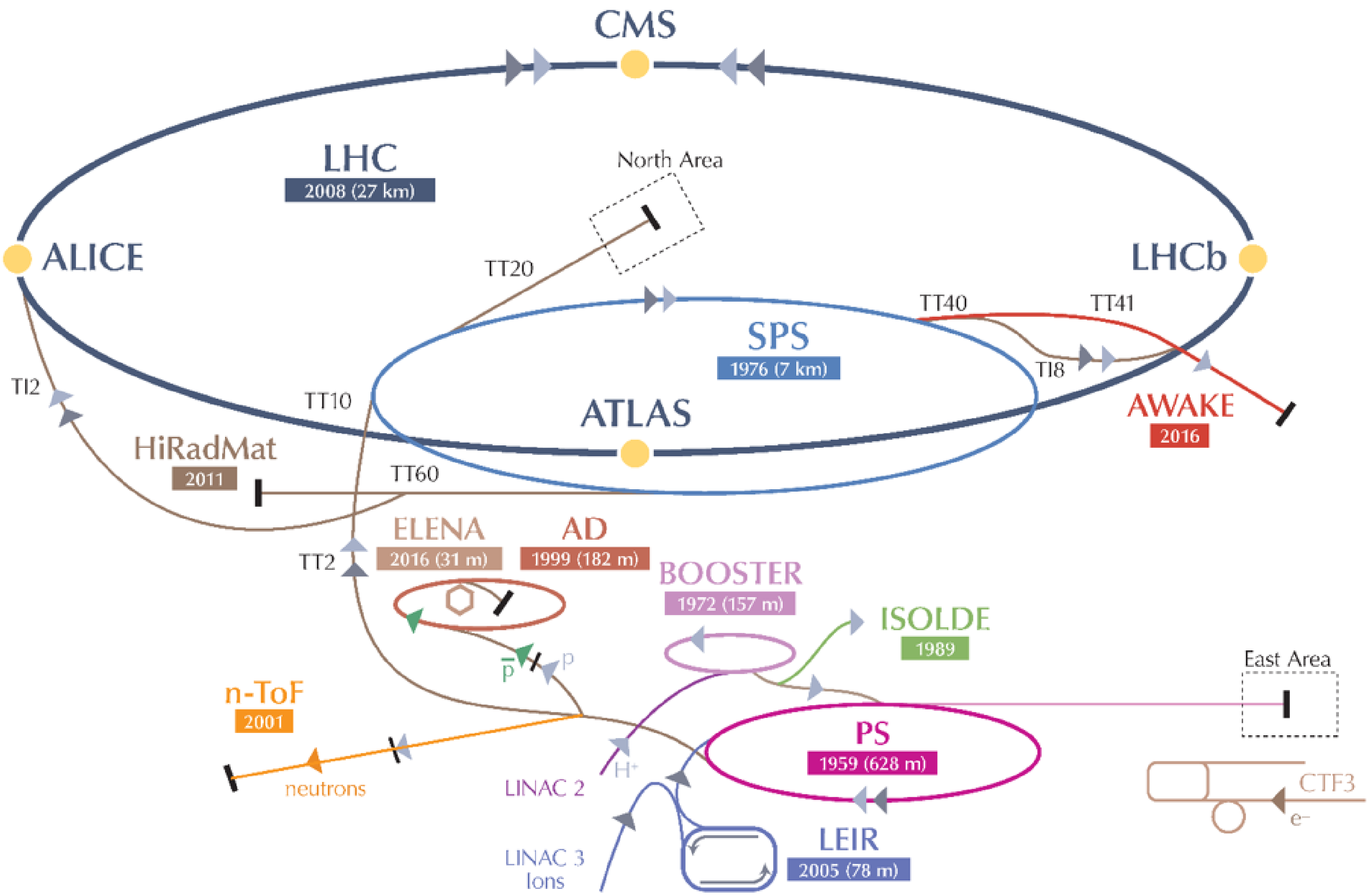
  - radioisotope production
- Industrial applications
- Environmental applications

Particle Accelerators

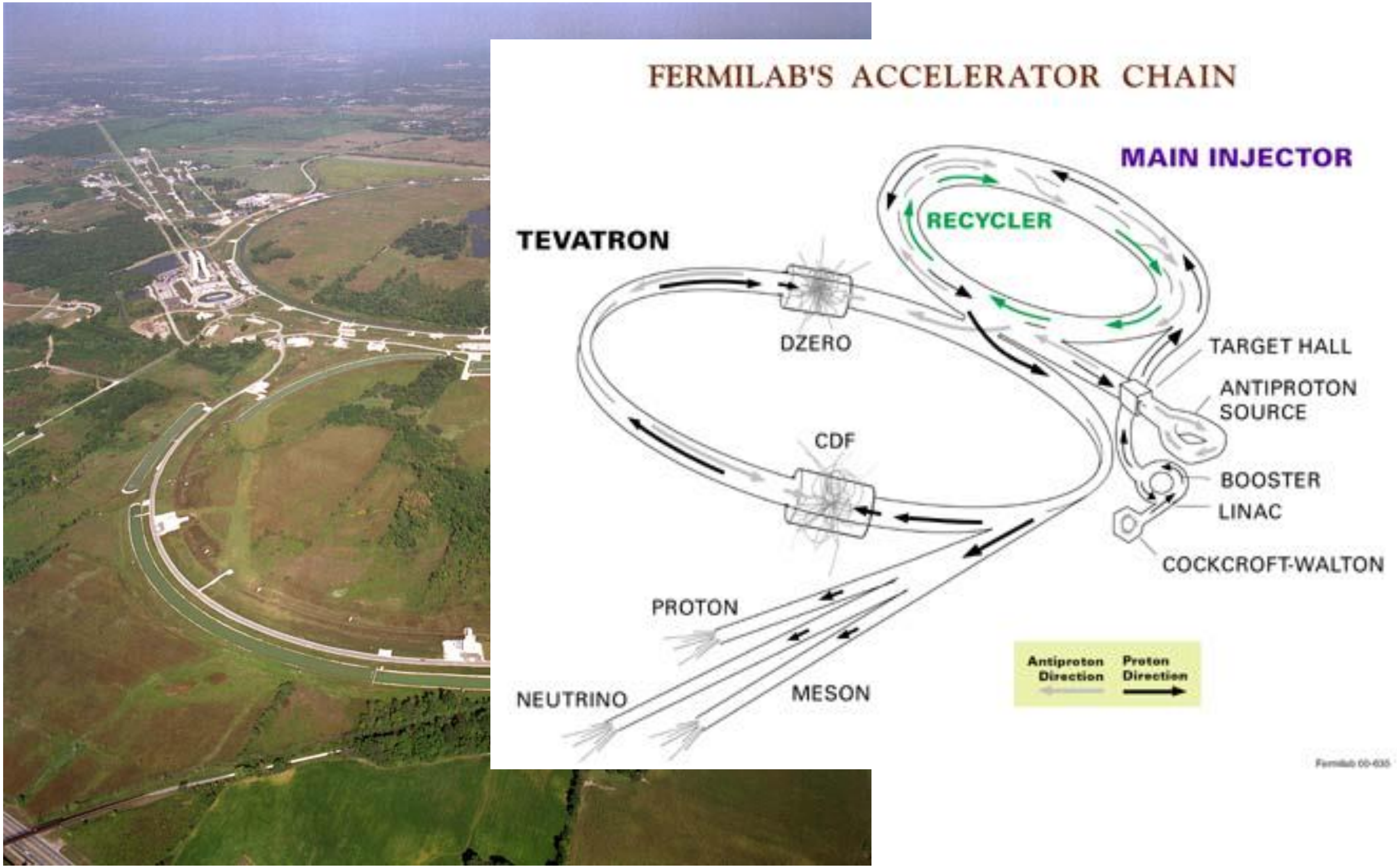
- For research, e.g. CERN, main requirements
  - energy
  - beam control (for luminosity, etc)
- Main accelerators used for protons:
  - linear accelerators at low energy
  - synchrotrons to get to higher energy

CERN

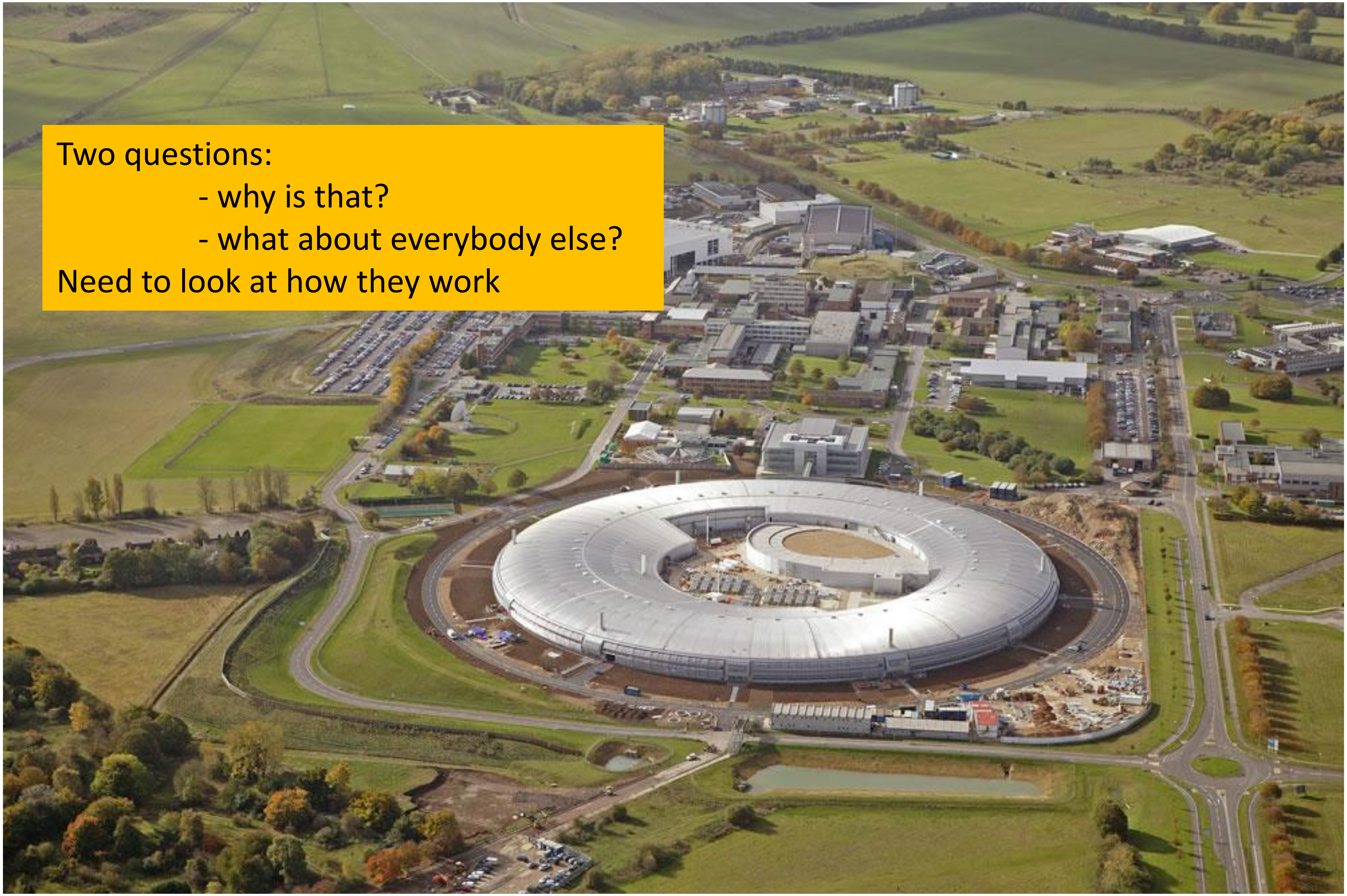
CERN's Accelerator Complex



Fermilab


FERMILAB'S ACCELERATOR CHAIN
MAIN INJECTOR
RECYCLER
TEVATRON
DZERO
CDF
TARGET HALL
ANTIPROTON SOURCE
BOOSTER
LINAC
COCKCROFT-WALTON
PROTON
NEUTRINO
MESON
Antiproton Direction
Proton Direction
Fermilab 00-635

RAL

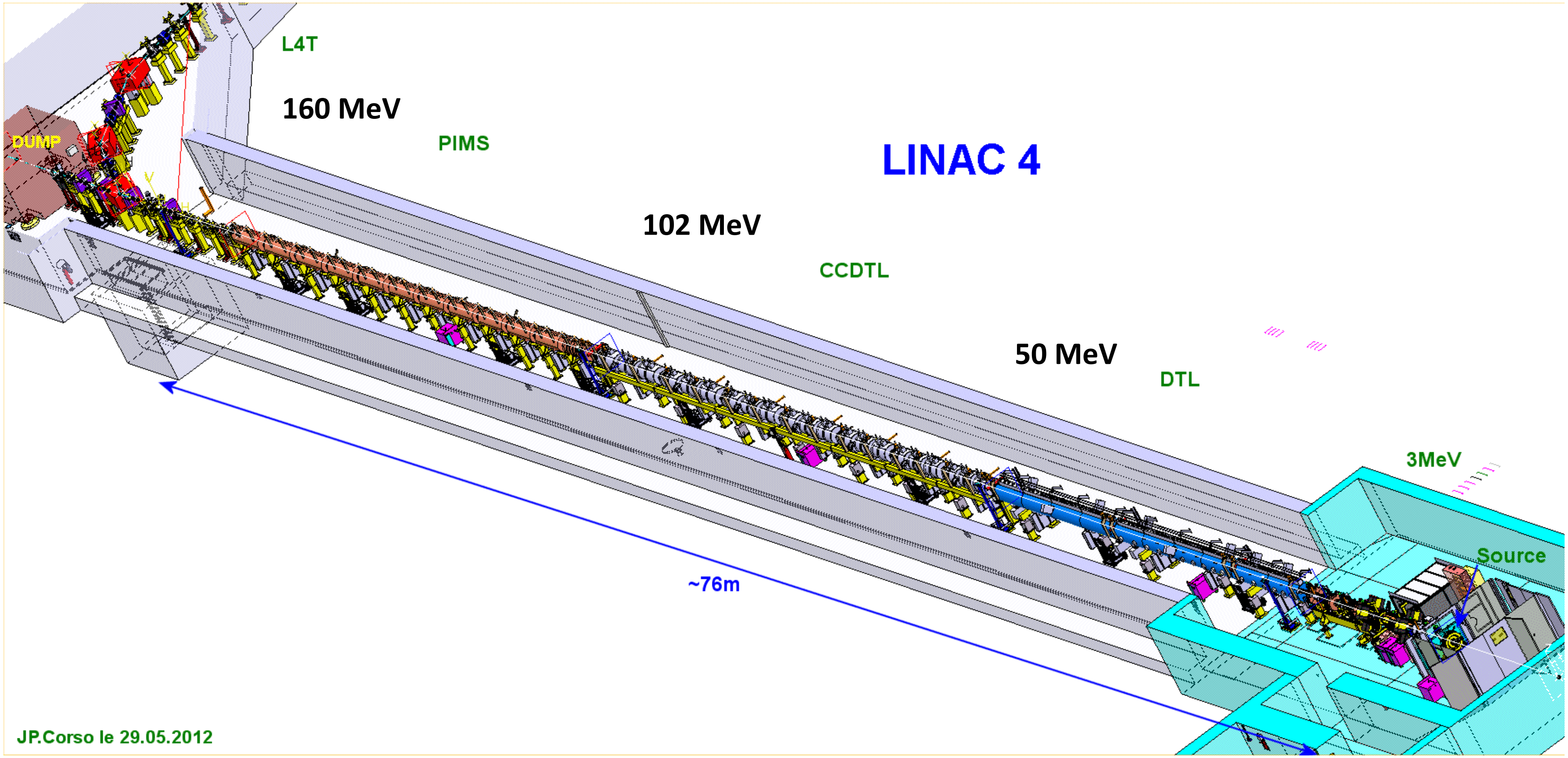


Two questions:

- why is that?
- what about everybody else?

Need to look at how they work

Linacs: how do they work?



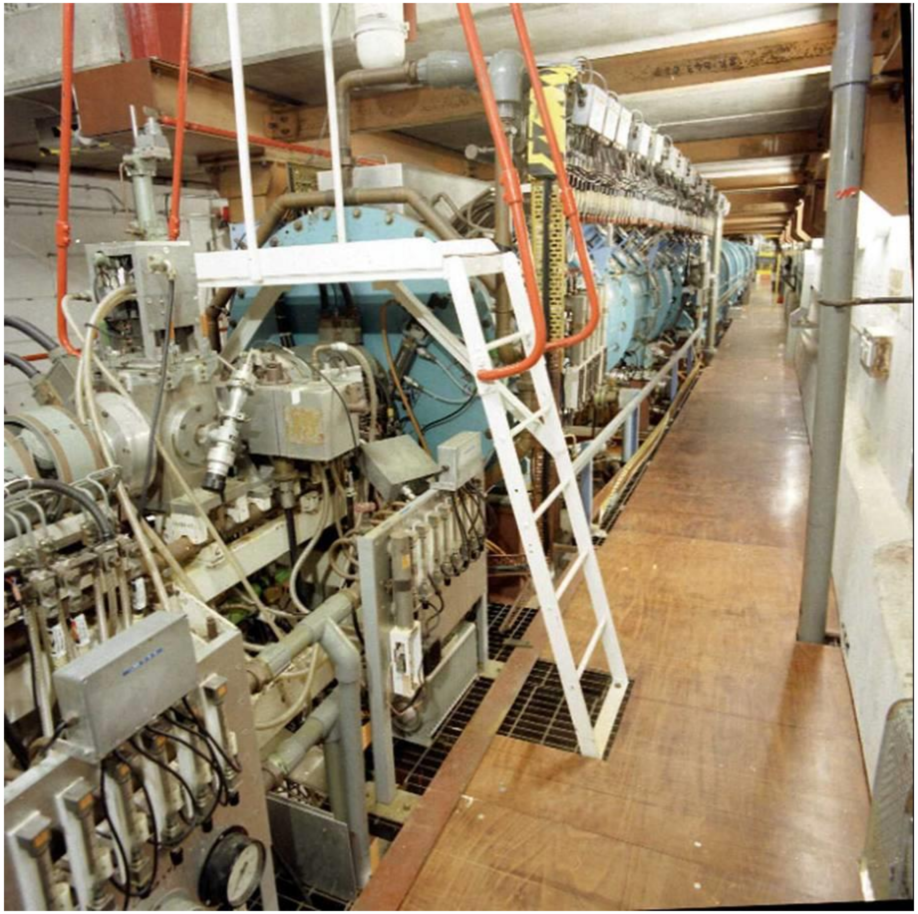
JP.Corso le 29.05.2012

Linacs: how do they work?

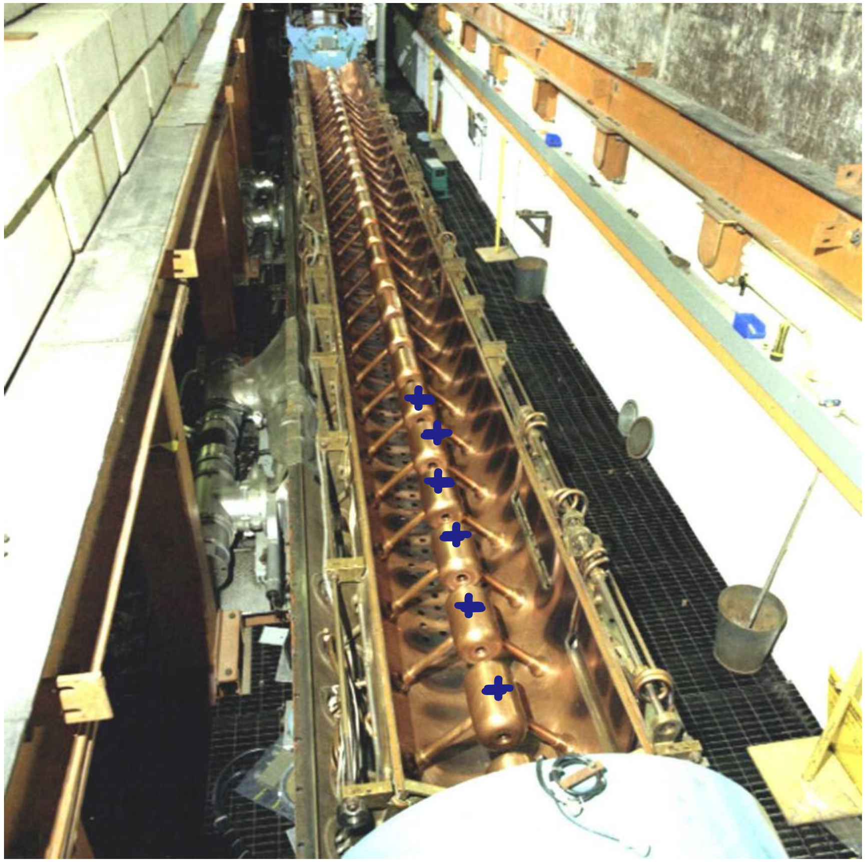
Linac4 DTL

Photo credits: CERN

Linear Accelerators

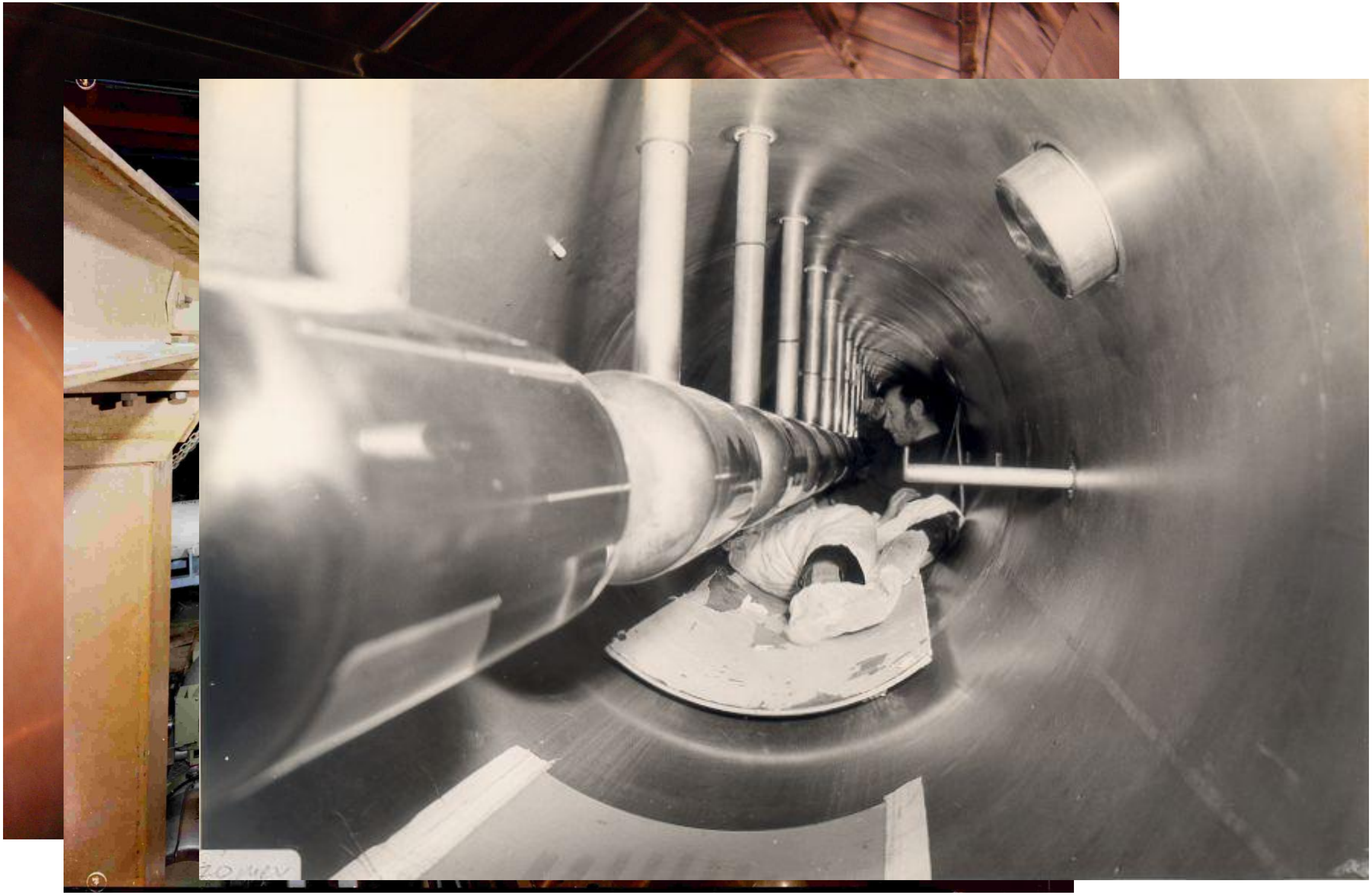


Acceleration via electric fields
AC frequency in the RF range



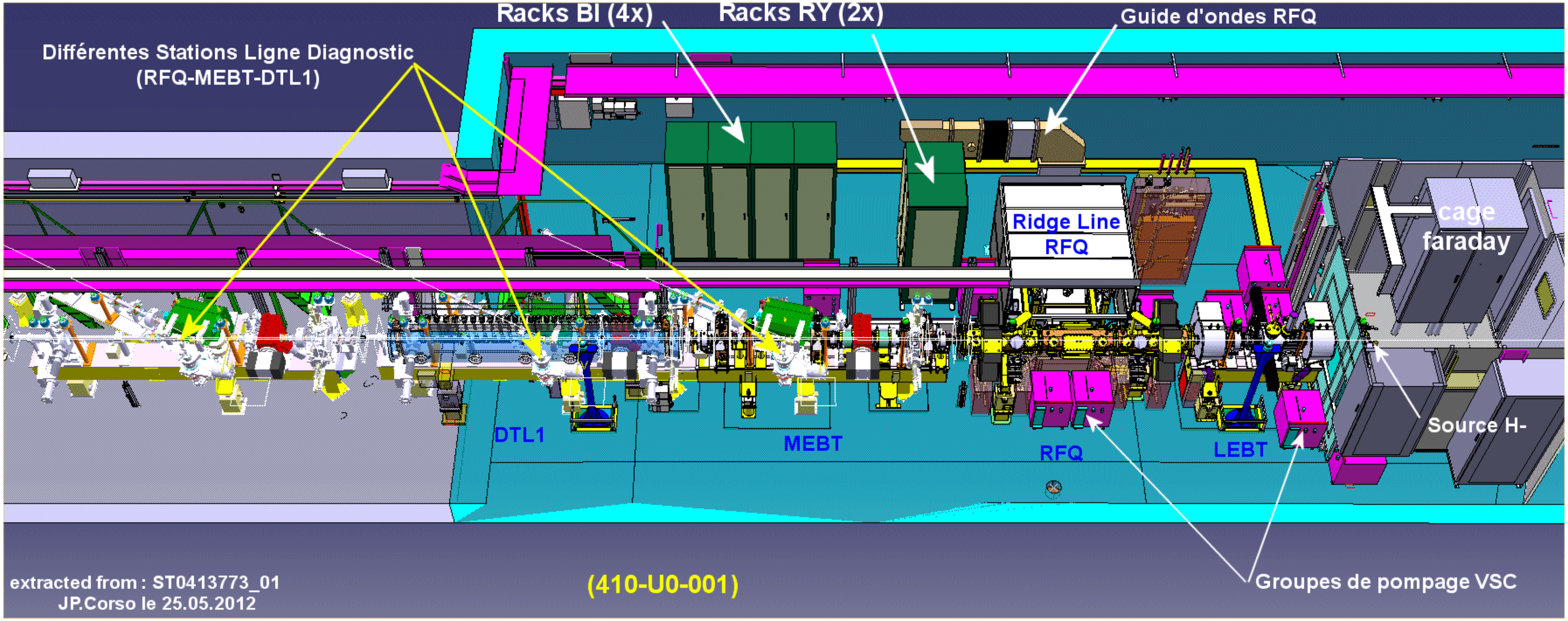
ISIS 70 MeV linac at RAL

Linear Accelerators



Linear Accelerators

Linac4 chopper (3 MeV) line

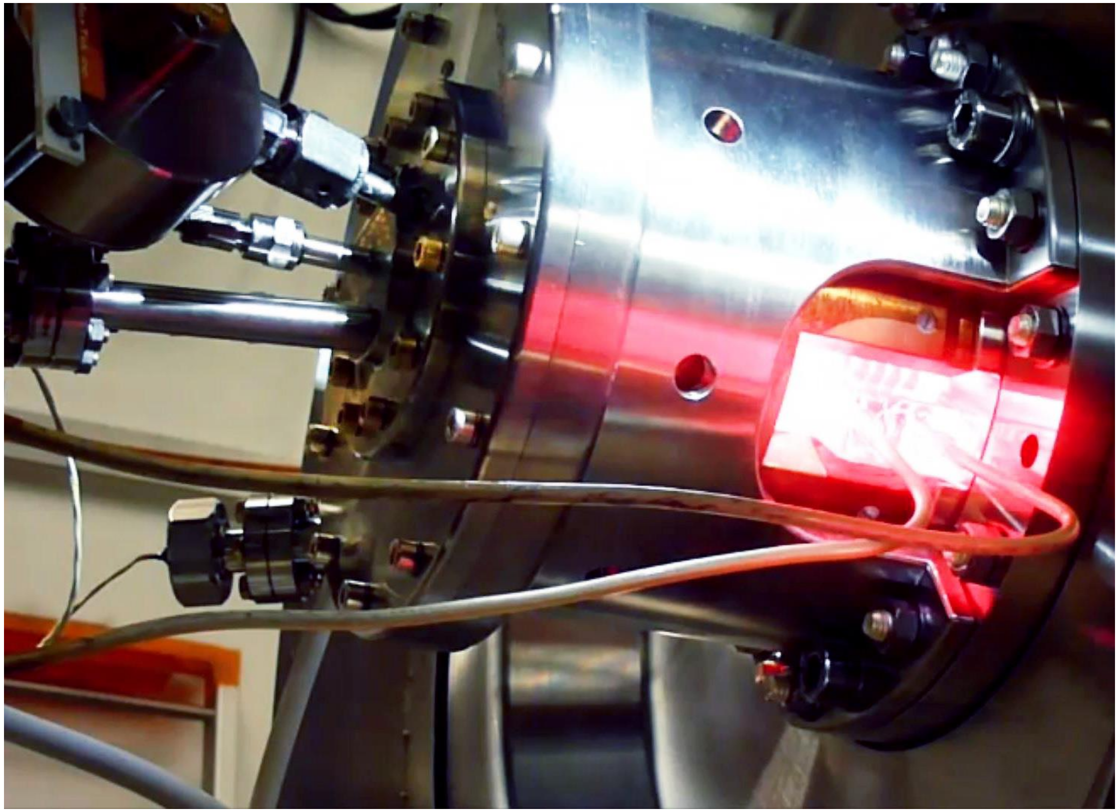


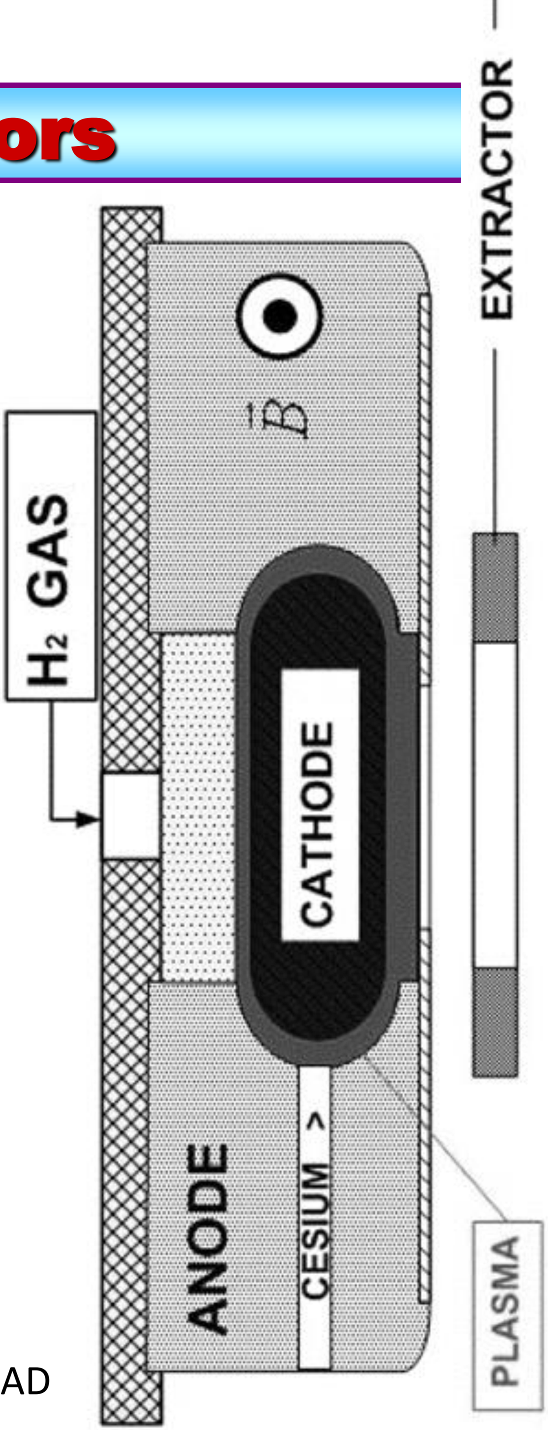
extracted from : ST0413773_01
JP.Corso le 25.05.2012

(410-U0-001)

Linear Accelerators

Linac4 H- ion source

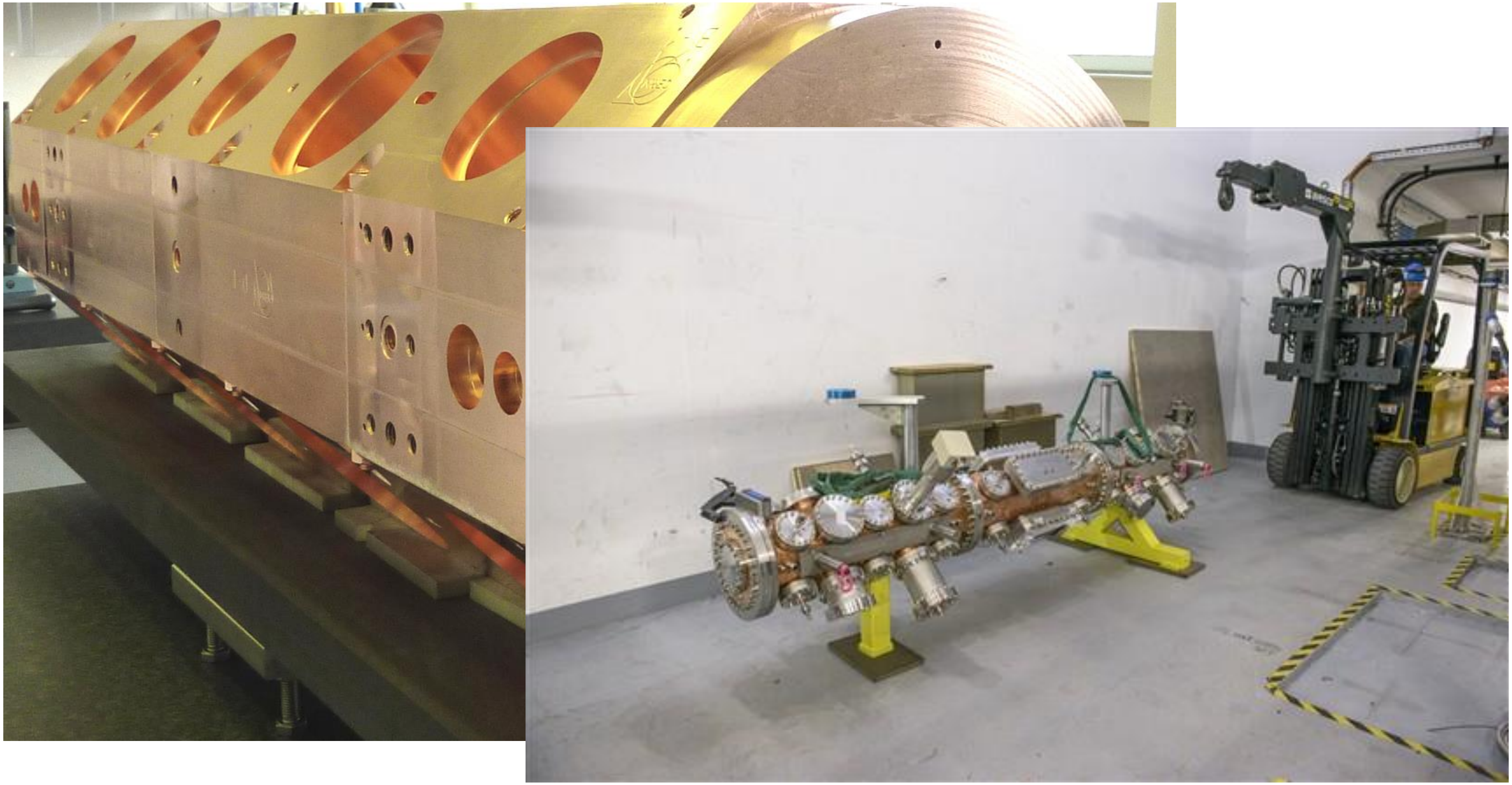




From Moehs et al, FERMILAB-PUB-05-094-AD

Linear Accelerators

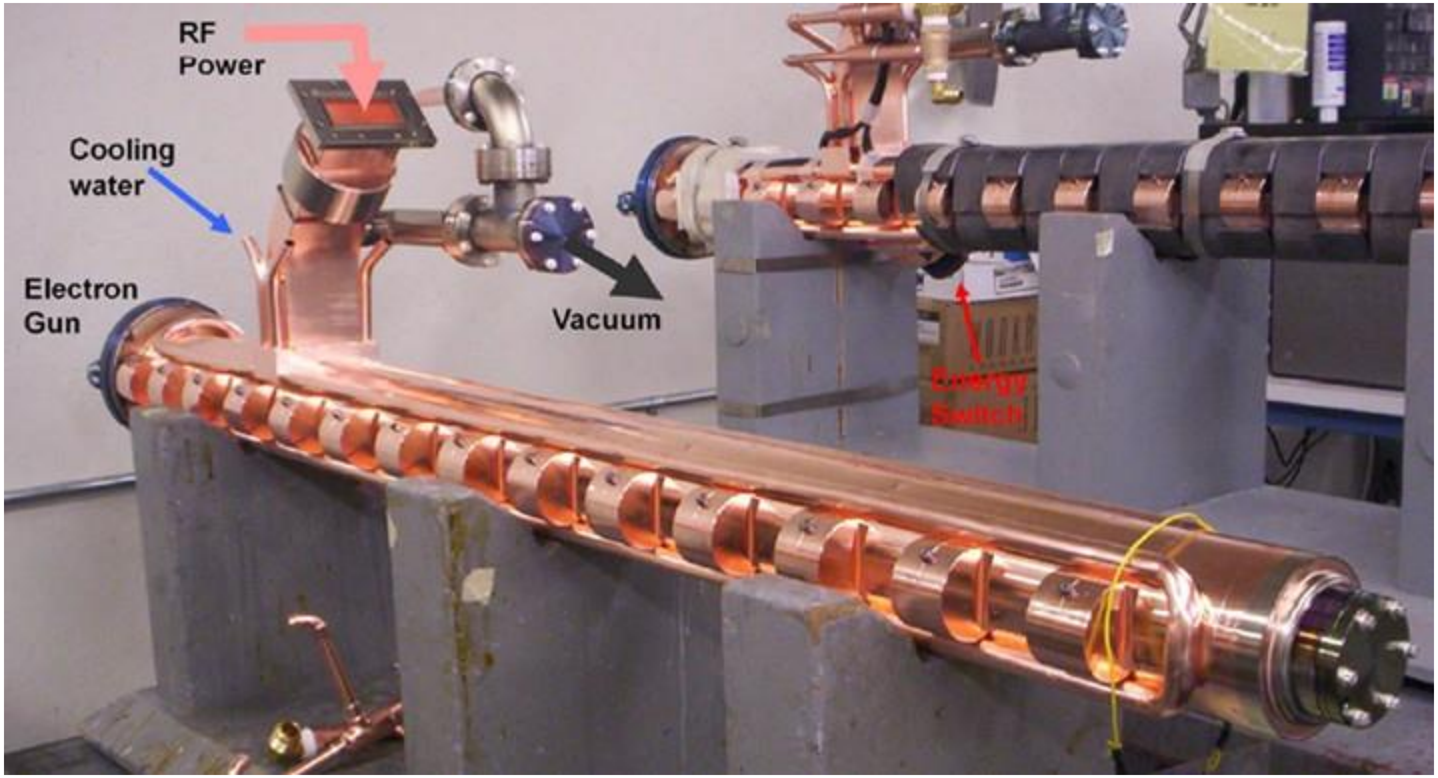
Linac4 Radio Frequency Quadrupole



Electron Linacs

- e- commonly produced by emission from heated cathode
- "Brighter" beam than for ions
- Higher frequency (smaller wavelength) RF possible:
  - higher accelerating gradients
  - smaller structures
- e- relativistic at low energy
- Electron linacs (for applications) smaller and simpler than ions

Electron Linacs



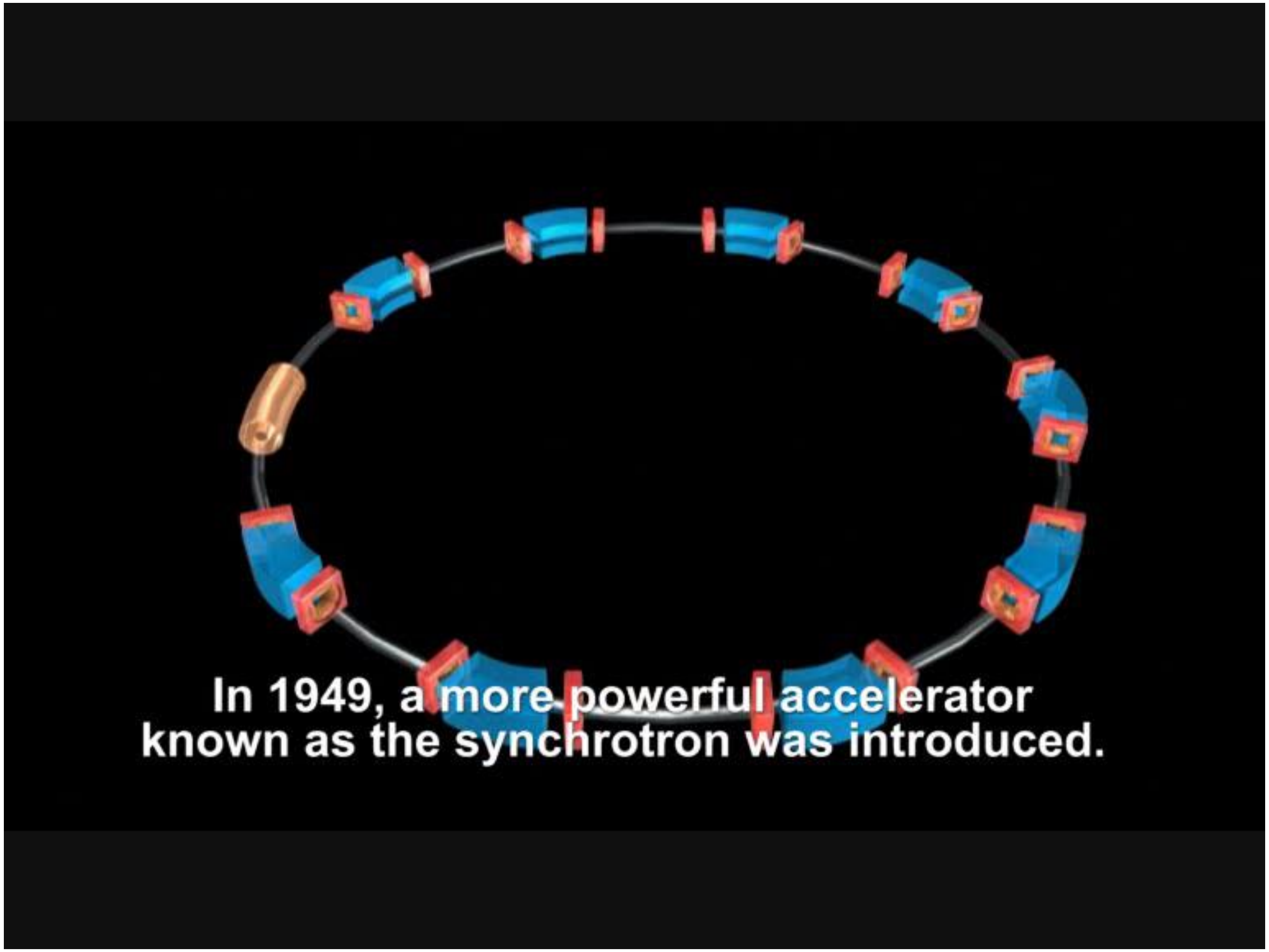
Varian Medical Linac

Linear Accelerators

- Advantages:
  - fixed RF frequency
  - fixed magnetic fields
  - easy to operate
  - reliable
  - good for non-relativistic particles
- Disadvantages:
  - each component used once per pass
  - long for high energies
  - expensive at higher energies
  - continuous operation has complications unless SC

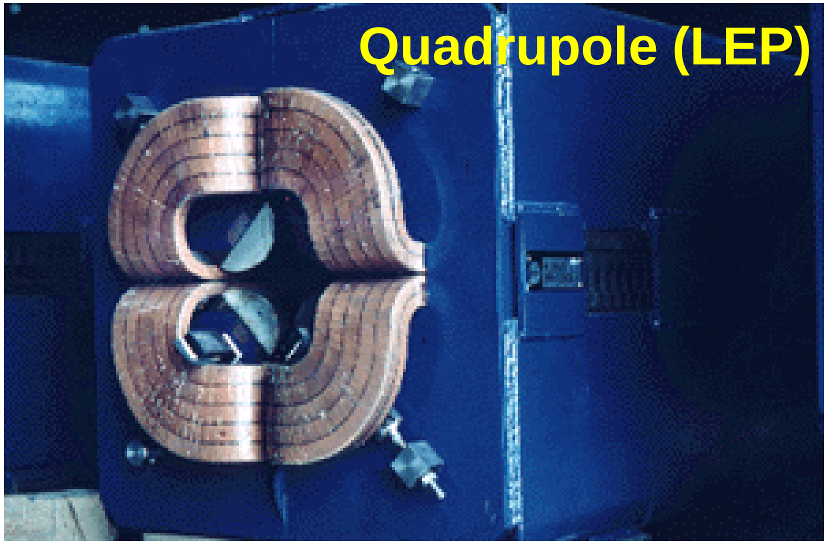
Synchrotrons

Circular accelerators:

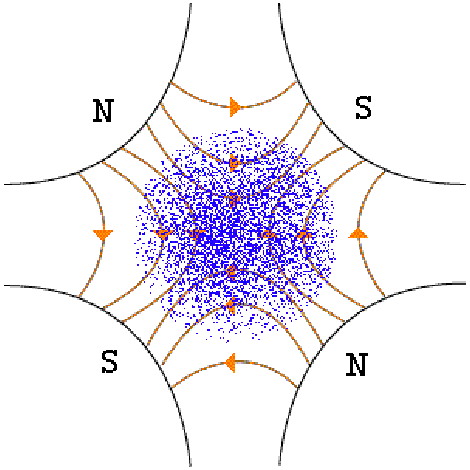


In 1949, a more powerful accelerator known as the synchrotron was introduced.

Strong Focussing

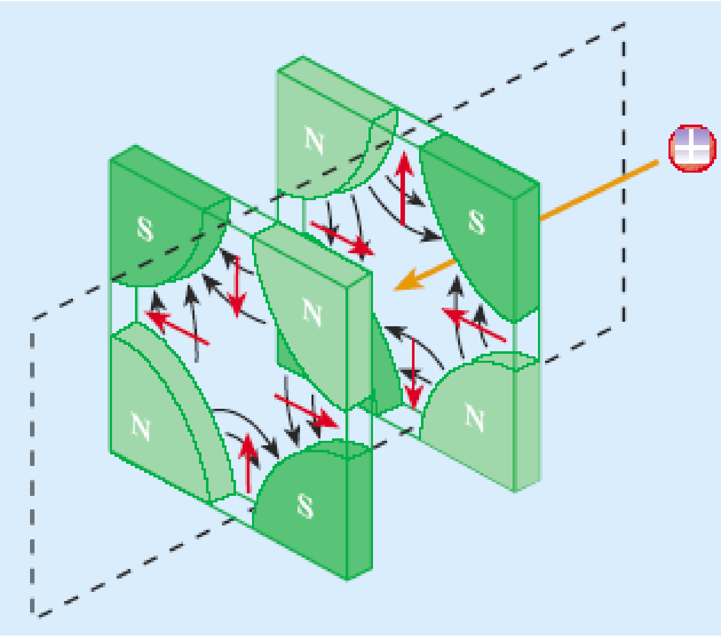


Quadrupole (LEP)



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

Sextupole (LEP)
Correction of chromatic spread.



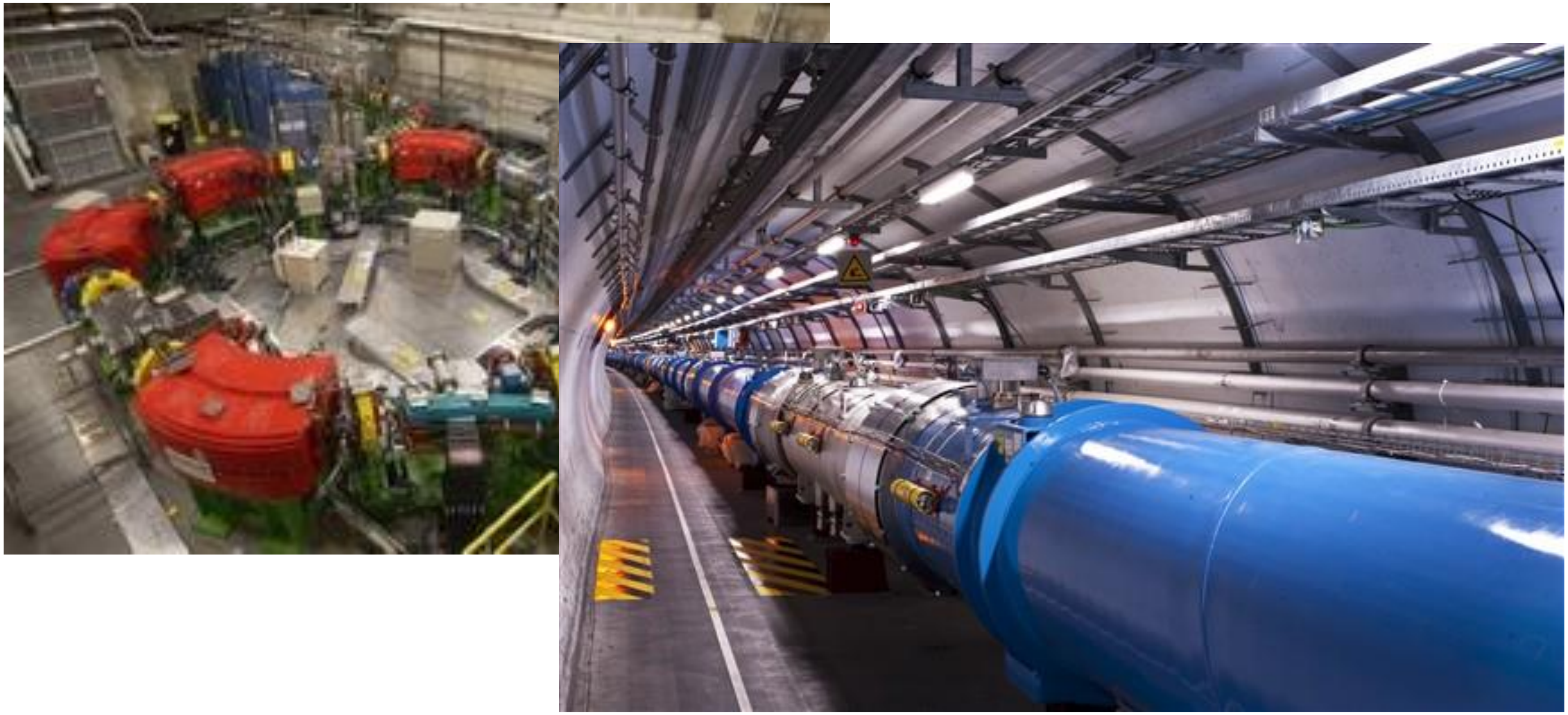
Strong Focussing

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	

Synchrotrons

Circular accelerators



Synchrotrons

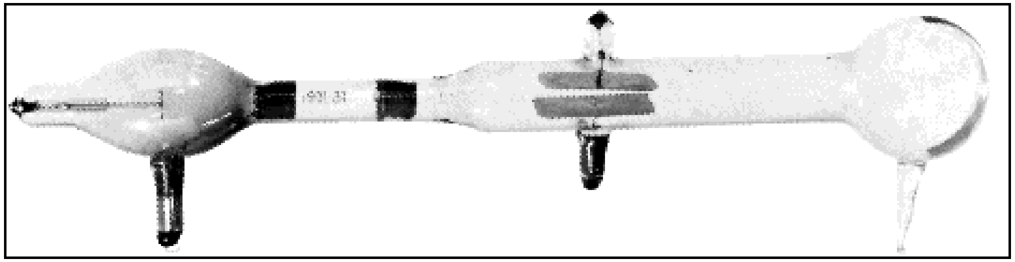
- Advantages:
  - very high energies possible
  - very good beam control
  - small machine aperture
- Disadvantages:
  - big
  - expensive
  - pulsed
  - variable frequency RF
  - not so easy to operate

Rest of the World

- Nearly 40000 accelerators in use
- About half < 5 MeV
- Nearly all of rest < 20 MeV
- About 2/3rd electrons, 1/3rd ion
- Used for a variety of applications
- Requirements different from HEP:
  - cost effective
  - reliable
  - easy to operate
  - current is usually more important than energy
- Three types of accelerator
  - electrostatic
  - linacs
  - cyclotrons

Electrostatic Accelerators

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

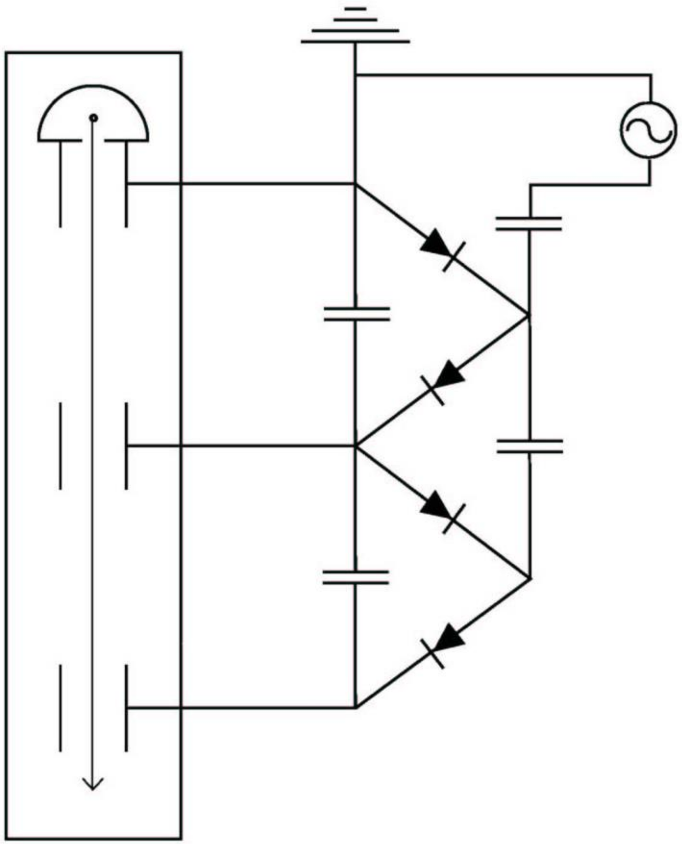


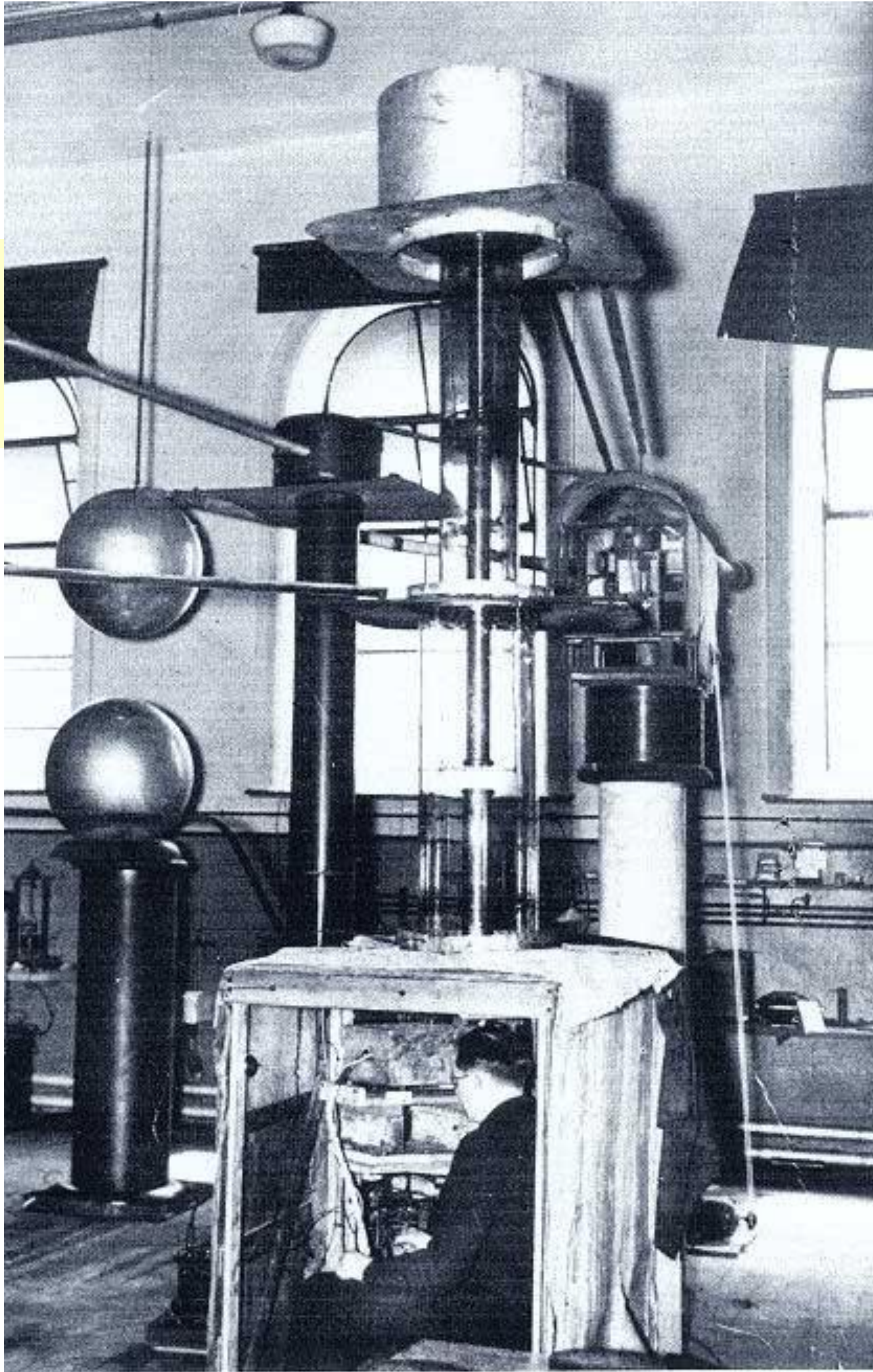
1897 – J.J. Thomson

Cathode ray tube

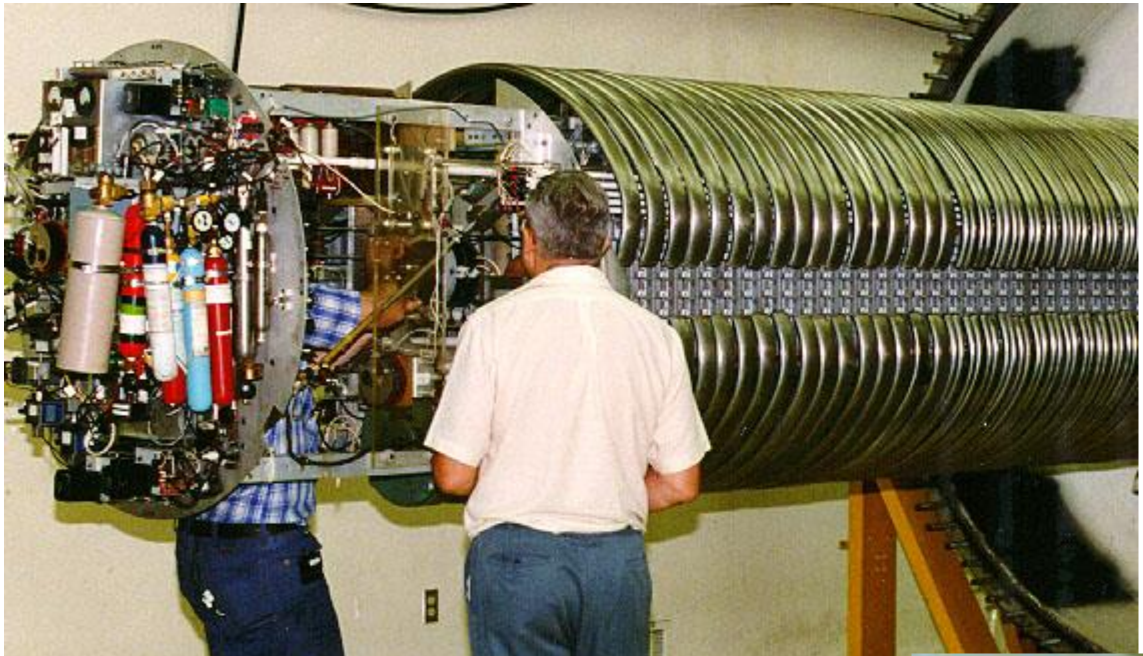
- Cockcroft Walton ~voltage multiplier
- Van der Graaff
- Tandem

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



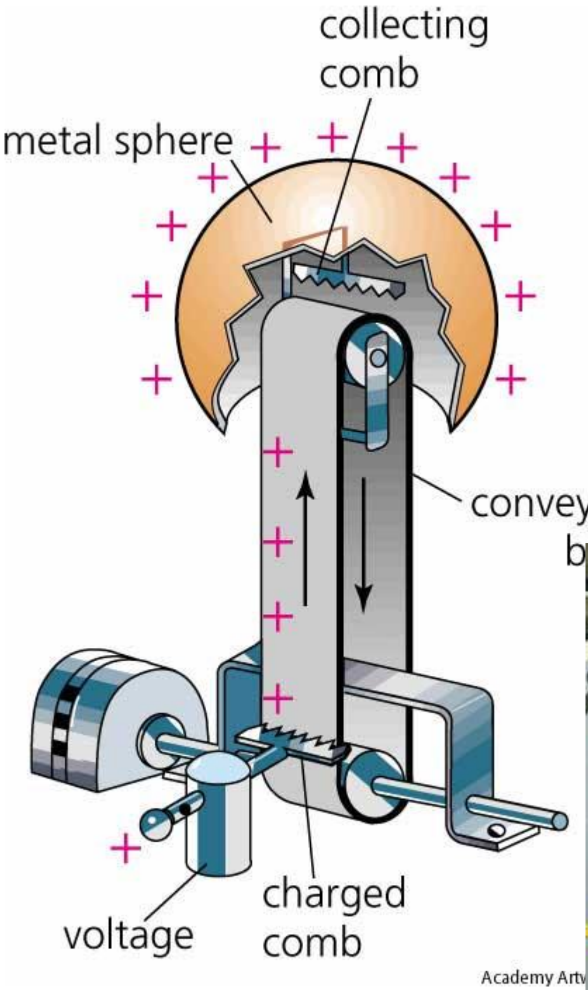


ISIS Cockcroft-Walton at RAL

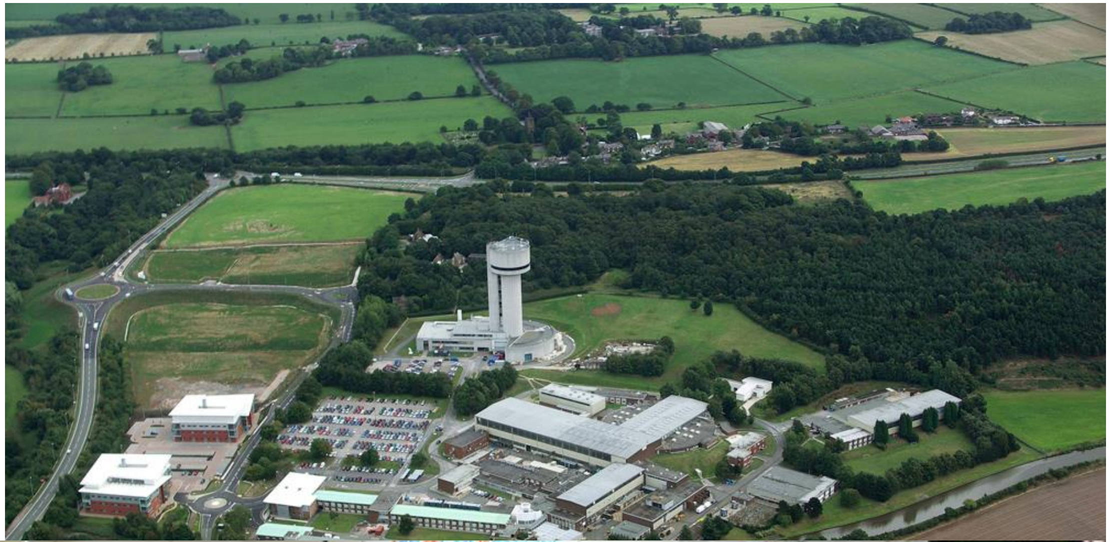


Dynamitron

Electrostatic Accelerators



Academy Art



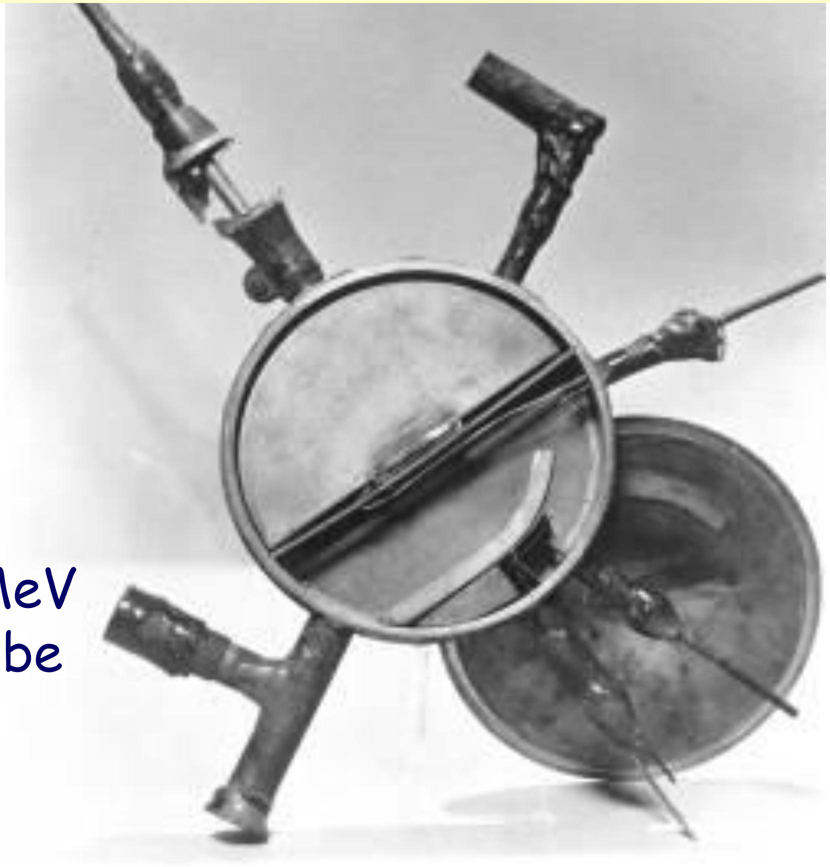
Electrostatic Accelerators

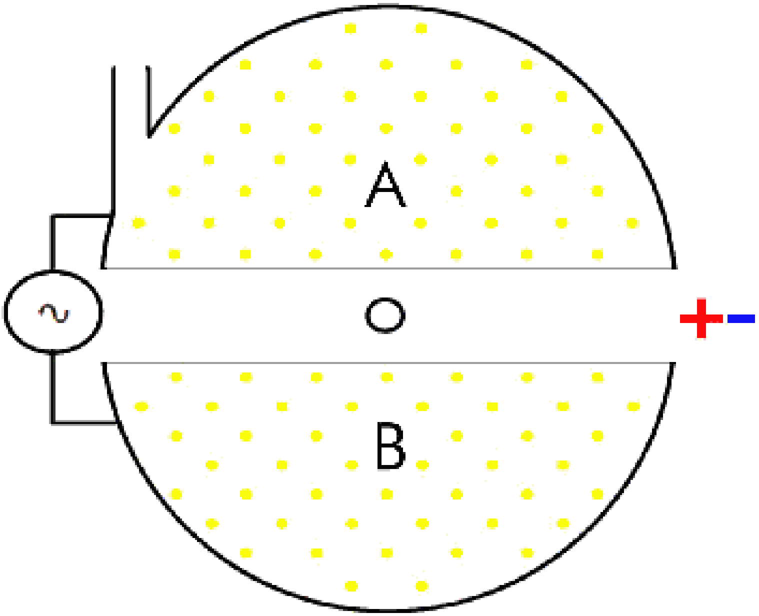
- Advantages:
  - DC
  - large beam currents possible
  - easy to operate
  - very efficient
  - reliable
- Disadvantages:
  - limited beam energy
  - high voltages

Cyclotrons

First circular particle accelerator built by Ernest O. Lawrence & Stanley Livingston at Berkeley in 1930.

Energy = 80 keV, Diameter = 13cm





Simple cyclotron: isochronous to 12 MeV
Above that, the magnetic field must be shaped

Cyclotrons

Three things to worry about:

- Isochronous:

$$B_{av}(r) \sim \gamma(r)$$

where

$$B_{av} = \langle B(\theta) \rangle$$

- Horizontal control/focussing:

To 1st order, horizontal tune

$$\nu_x^2 \approx 1 + k$$

where average field index k

$$k(r) \equiv \frac{r}{B_{av}} \frac{dB_{av}}{dr}$$

- Vertical control/focussing:

To 1st order, vertical tune

$$\nu_y^2 \approx -k + F(1 + 2\tan^2 \varepsilon)$$

where flutter

$$F \equiv \left\langle \left(\frac{B(\theta)}{B_{av}} - 1 \right)^2 \right\rangle$$

→ Azimuthally Varying Field cyclotrons by L.H.Thomas in 1938

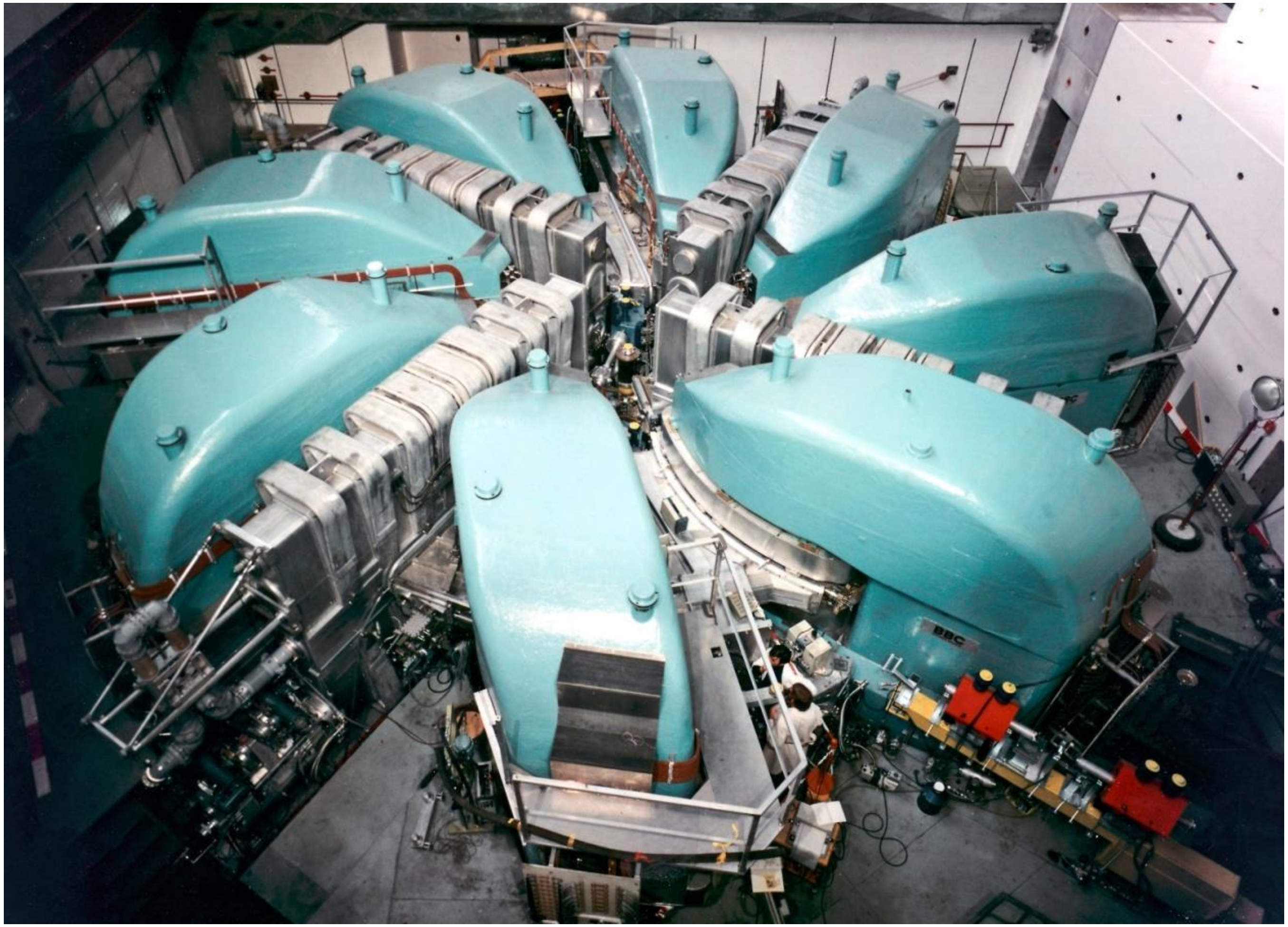
Cyclotrons

Images courtesy
GE and IBA

230 MeV IBA

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

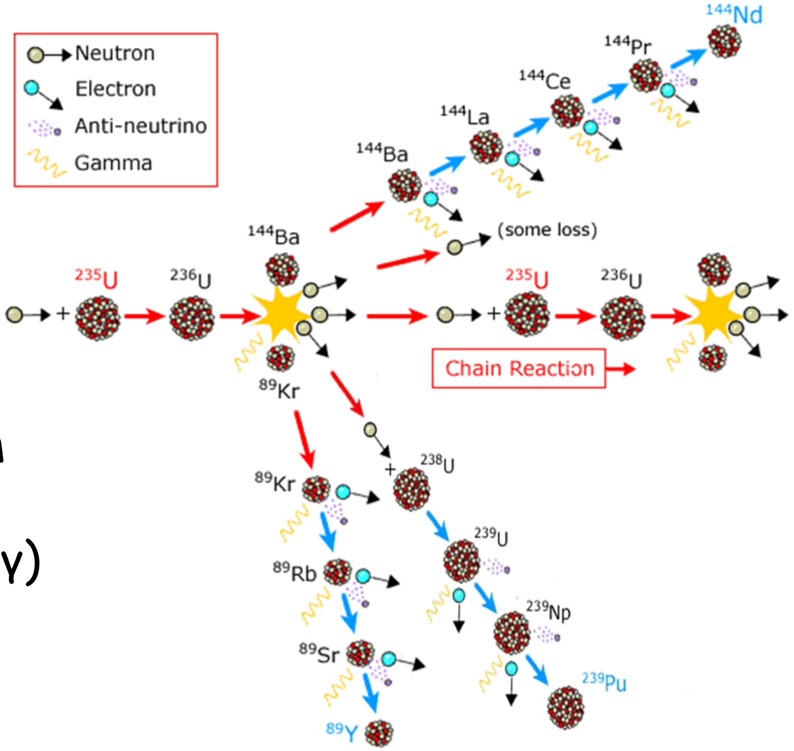
- Accelerators created for Particle Physics
- Many developments driven by PP
- Now used for other applications
  - ~40000 accelerators already in use around the World
  - Annual sales: >$3.5B
  - Annual product, etc, sales: >$0.5T
  - Fit into a few broad categories:
    - Energy
    - Environment
    - Healthcare
    - Industry
    - Security and defence
    - Research

Energy Applications

- All at an early stage
- Fission:
  - waste burners
  - thorium energy amplifiers
- Fusion:
  - plasma heating
  - materials studies
  - heavy ion inertial fusion

Fission

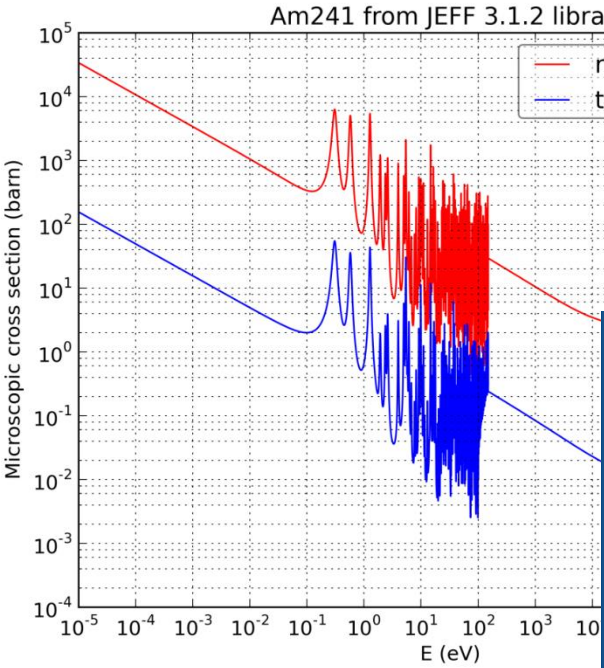
- (Almost) all fission reactors employ uranium-235 as fuel
- Related problems
  - only 0.7% of natural uranium → enrichment
  - proliferation: plutonium production
  - safety
  - uranium supply is not infinite
  - waste



Main waste issue:

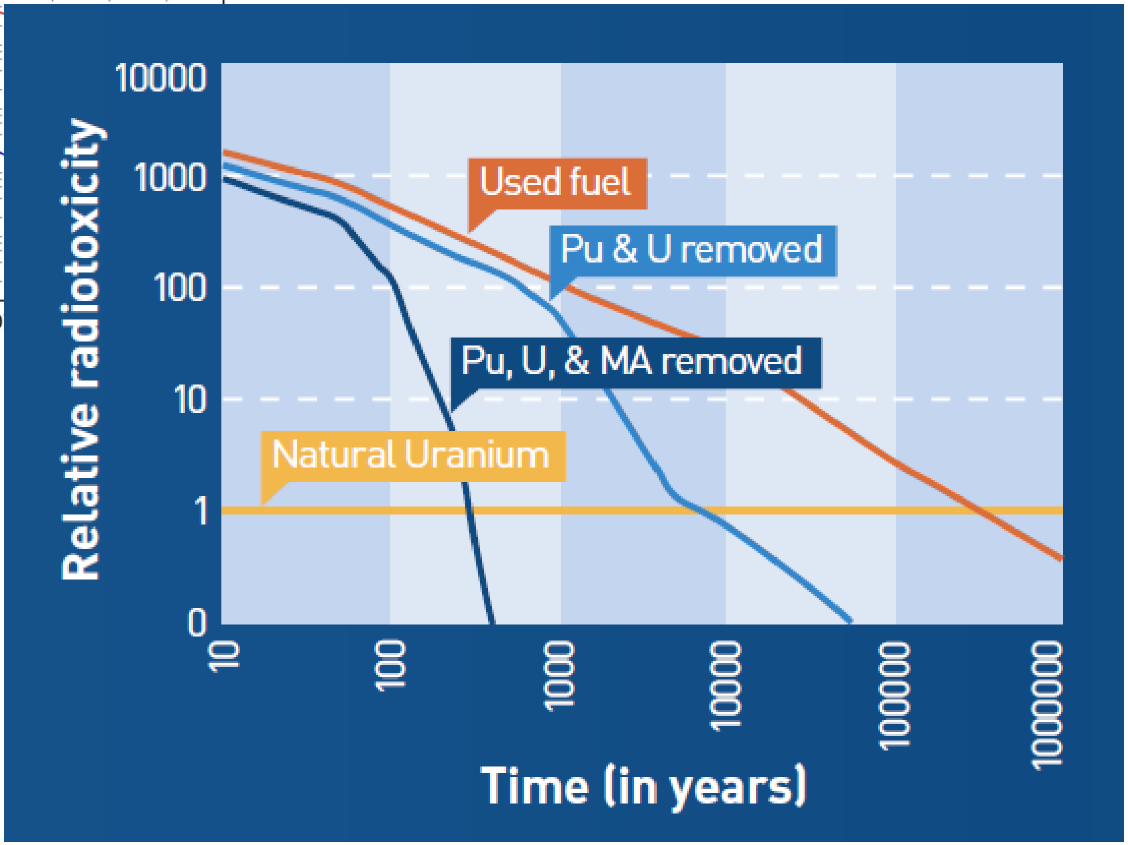
Minor Actinides ^{237}Np, ^{241}Am, Cm
- long lived >1000 years
- very radiotoxic (α, high energy γ)
- very hot

Fission



MAs are fissile

Fast neutron spectrum is essential



Requirements for ADS

- Sufficient beam energy for neutron spallation
- Sufficient beam current

Beam power:
≥ 4 MW

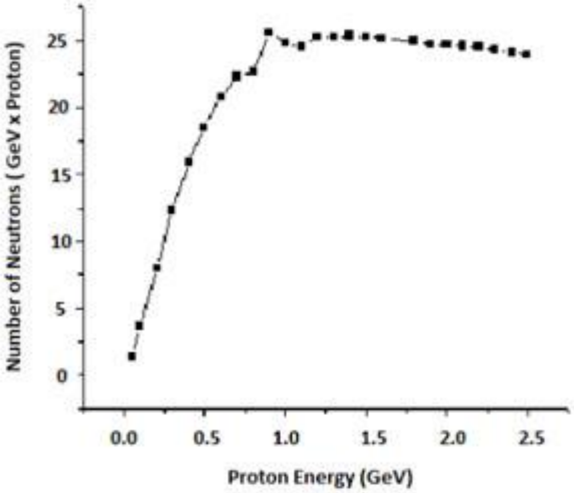
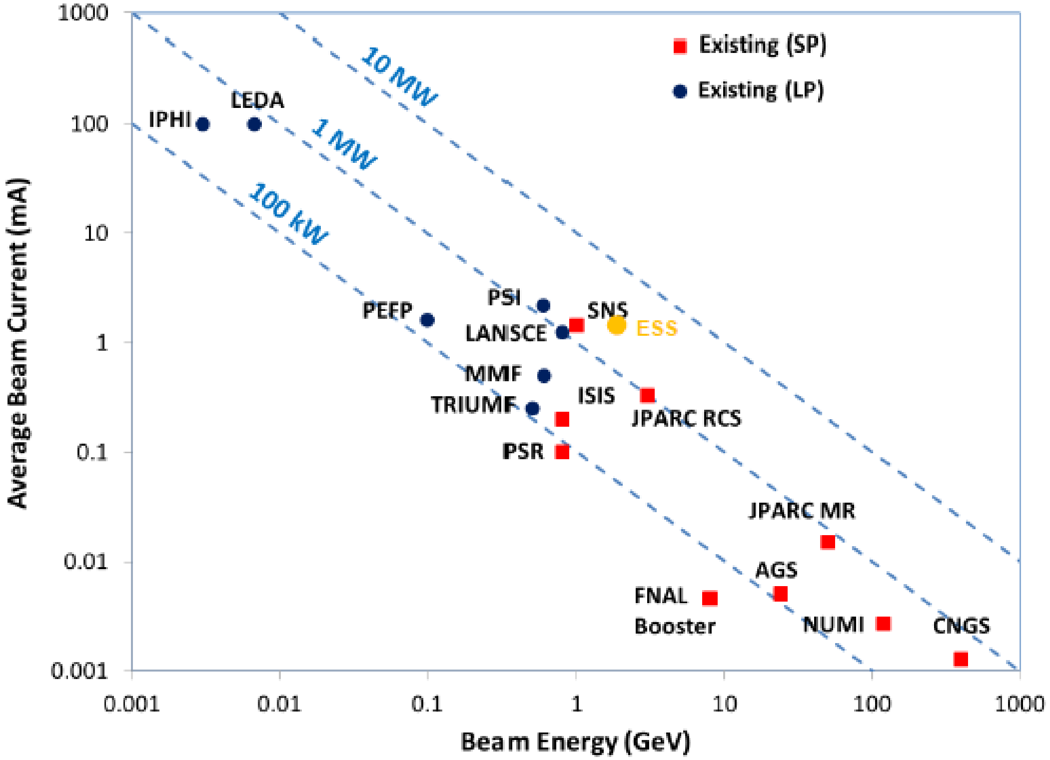


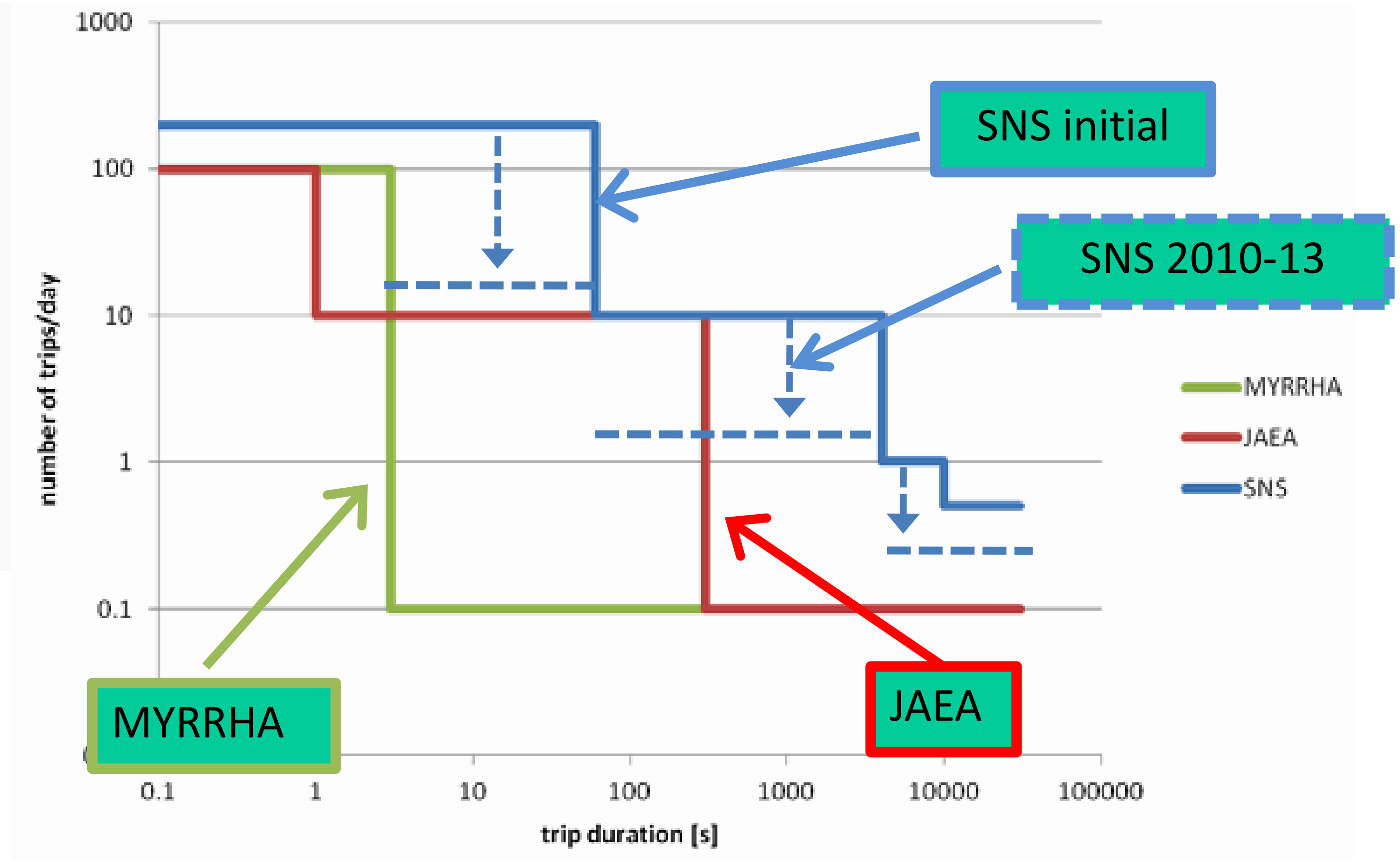
FIG. 2: Neutron multiplicity per unit energy and per incident proton as a beam energy for a LBE target.

Barros et al, Braz. J. Phys. vol.40 no.4 São Paulo Dec. 2010



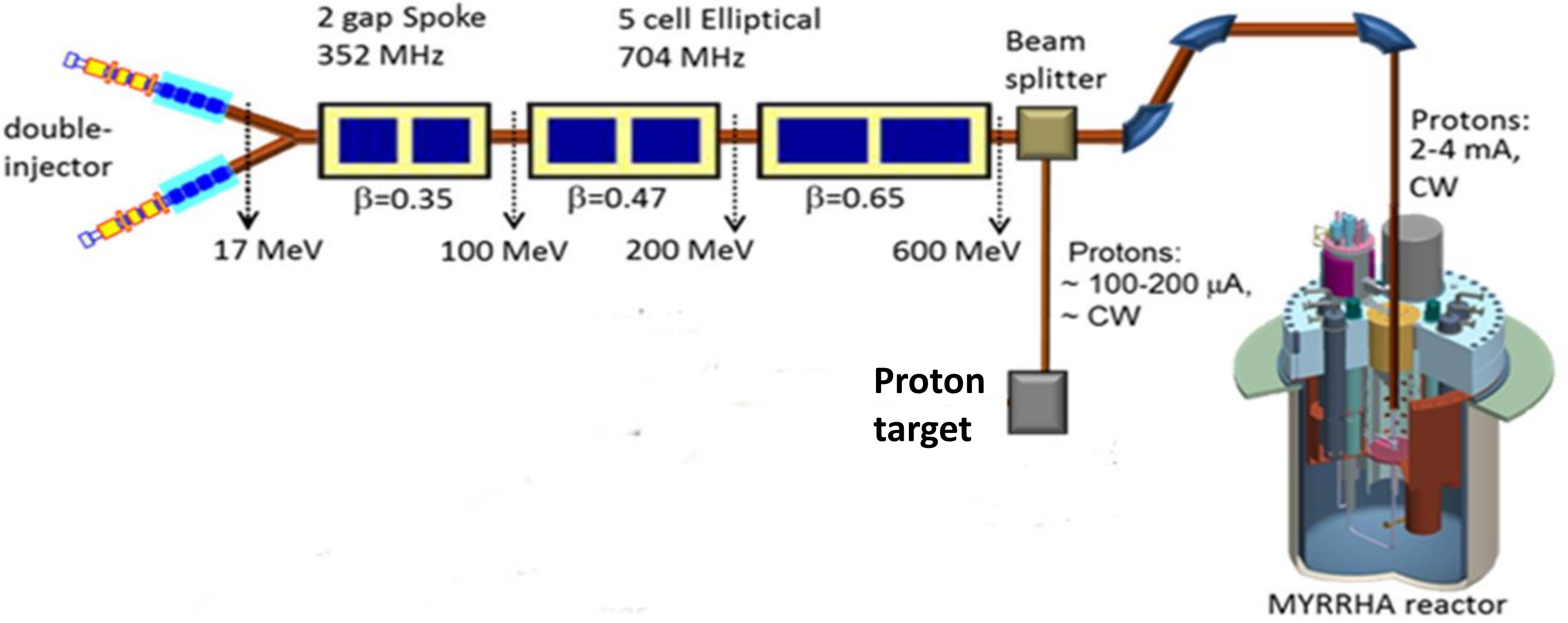
Requirements for ADS

- Sufficient beam reliability



Example Projects

- MYRRHA in Belgium: - 600 MeV, 1.5 MW
  - SC proton linac
  - lead-bismuth eutectic target



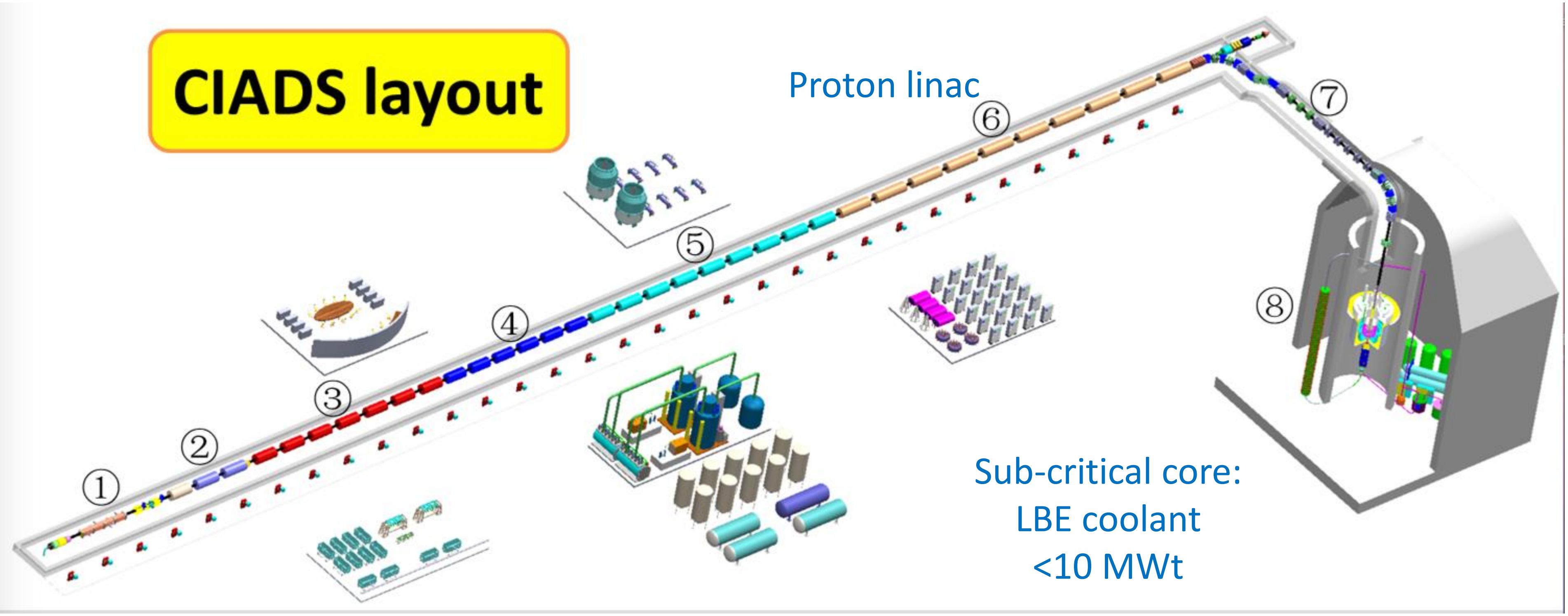
- Timescale: - 100 MeV accelerator in 2024
  - decision on next steps

Chinese ADS

- China: largest energy consumer in world; 79% coal in 2011
- Nuclear power:
  now: 22 reactors working (18GWe), 27 construction (27GWe)
  2020: 58 GWe (with 30 GWe under construction)
  2050: 350-400 GWe (~ total world production in 2014)
- ADS project:
  - 250 to 600 MeV
  - 2.5 mA
  - CW superconducting proton linac
  - flowing granular target

Chinese ADS

Granular target



Proton linac

Sub-critical core:
LBE coolant
<10 MWt

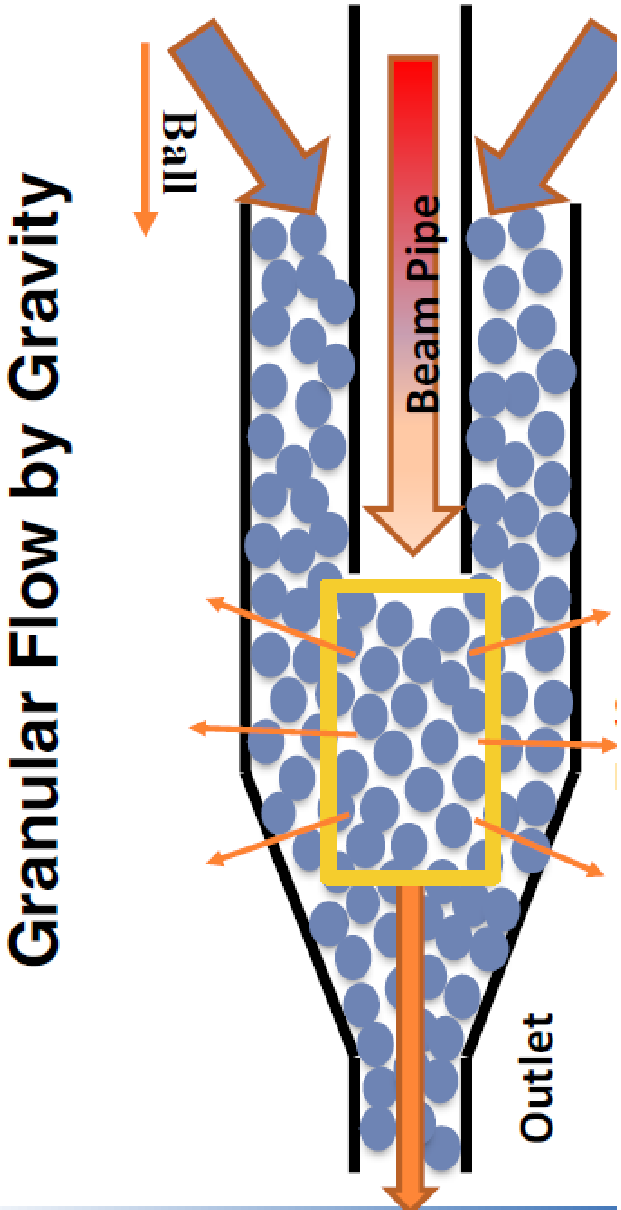
① Ion source+LEBT+RFQ+MEBT
② HWR009 section
③ HWR019 section
④ Spoke042 section
⑤ Elliptical062 section
⑥ Elliptical082 section
⑦ Coupling section
⑧ Reactor

Chinese ADS

- Aim: initial facility (>250 MeV, 10 mA, <10 MWt) – 2022
  demo facility (1 GeV, <15mA, >500 MWt – 2030)
- Currently prototyping

10 MeV beam being commissioned

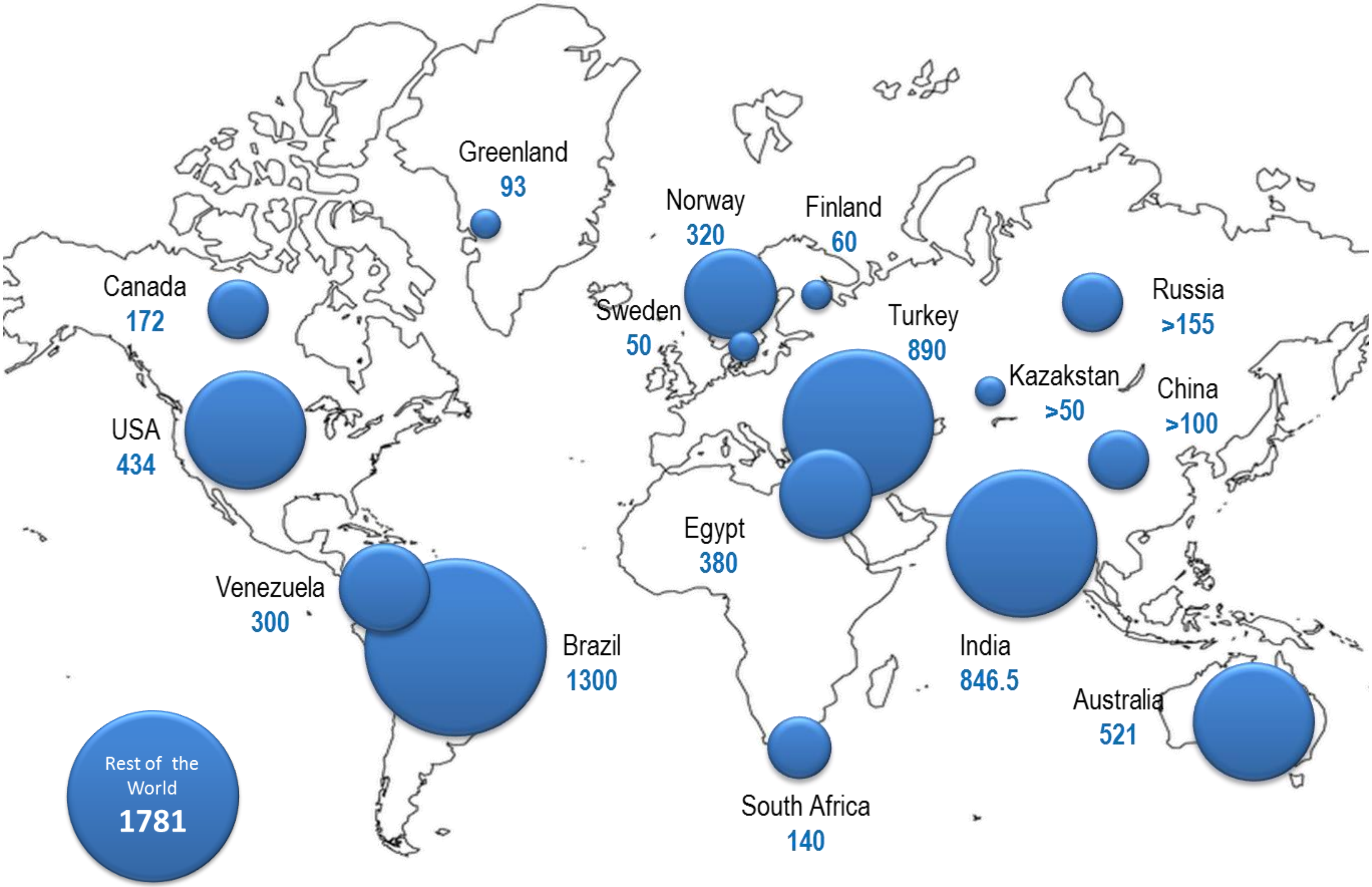
Chinese ADS



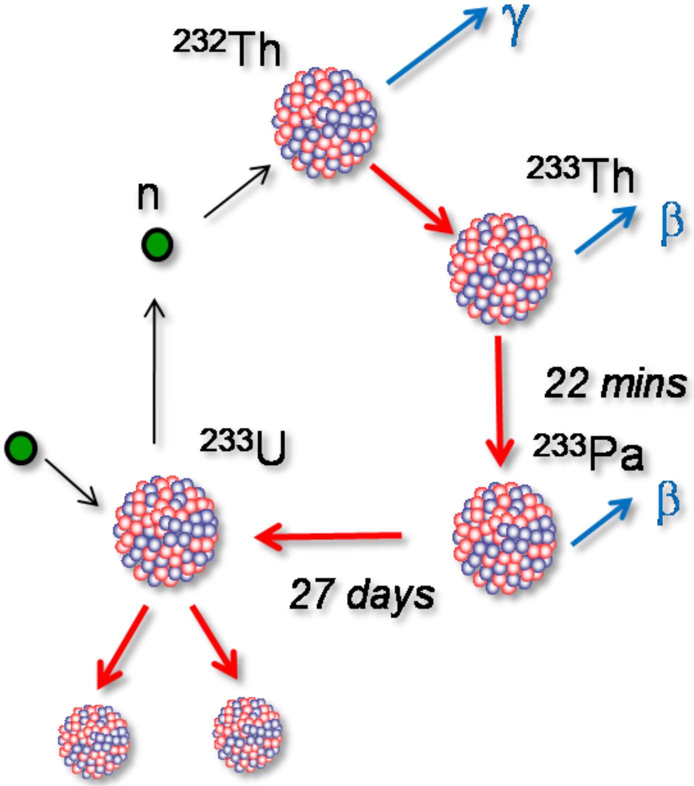
Thorium

- ^{235}U problems
  - only 0.7% of natural uranium → enrichment
  - proliferation: plutonium production
  - uranium supply is not infinite
  - waste
- Alternative fuel: thorium
  - 3*uranium in the Earth's crust, all burnt as fuel:
    1 ton Th ~ 200 tons U ~ 3500000 tons coal [Carlo Rubbia]
    about same amount in crust as lead
  - proliferation resistant (no Pu)
  - 50% of waste for storage
  - but.........sub-critical

Known Resources (ktonnes)

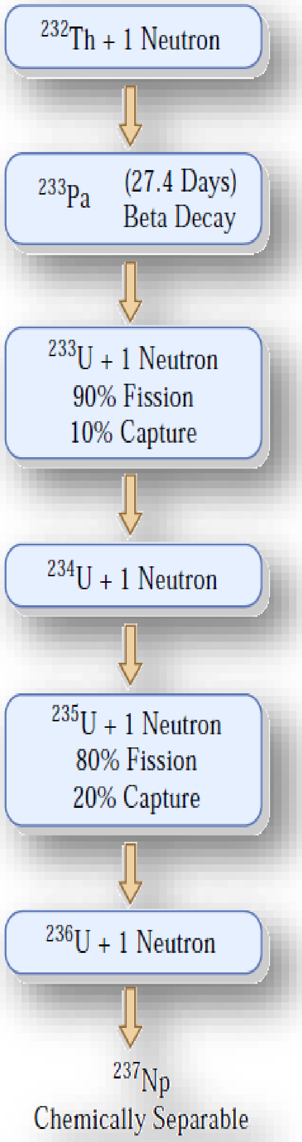


Thorium Fuel Cycle



Sub-criticality – must make more neutrons.
One method: an accelerator ~ 10 MW

But, currently, there is only really talk about this, little actual activity



^{232}Th + 1 Neutron

^{233}Pa (27.4 Days) Beta Decay

^{233}U + 1 Neutron
90% Fission
10% Capture

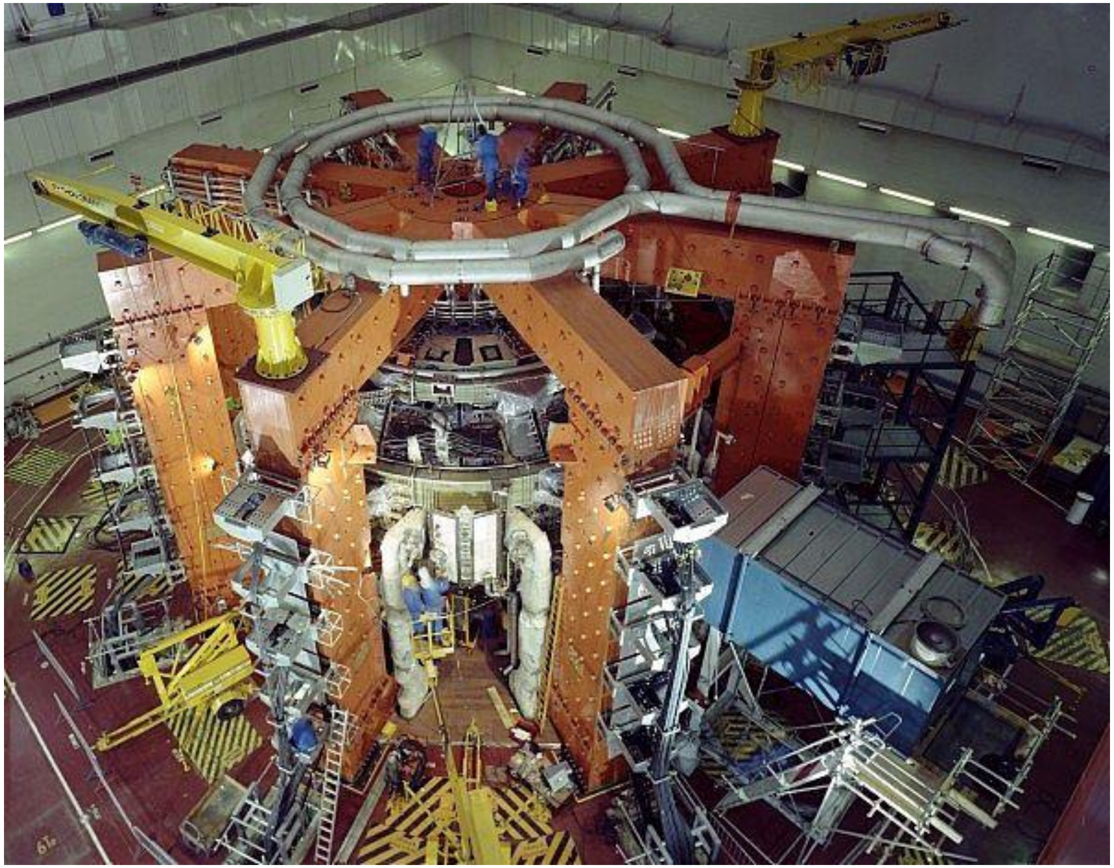
^{234}U + 1 Neutron

^{235}U + 1 Neutron
80% Fission
20% Capture

^{236}U + 1 Neutron

^{237}Np
Chemically Separable

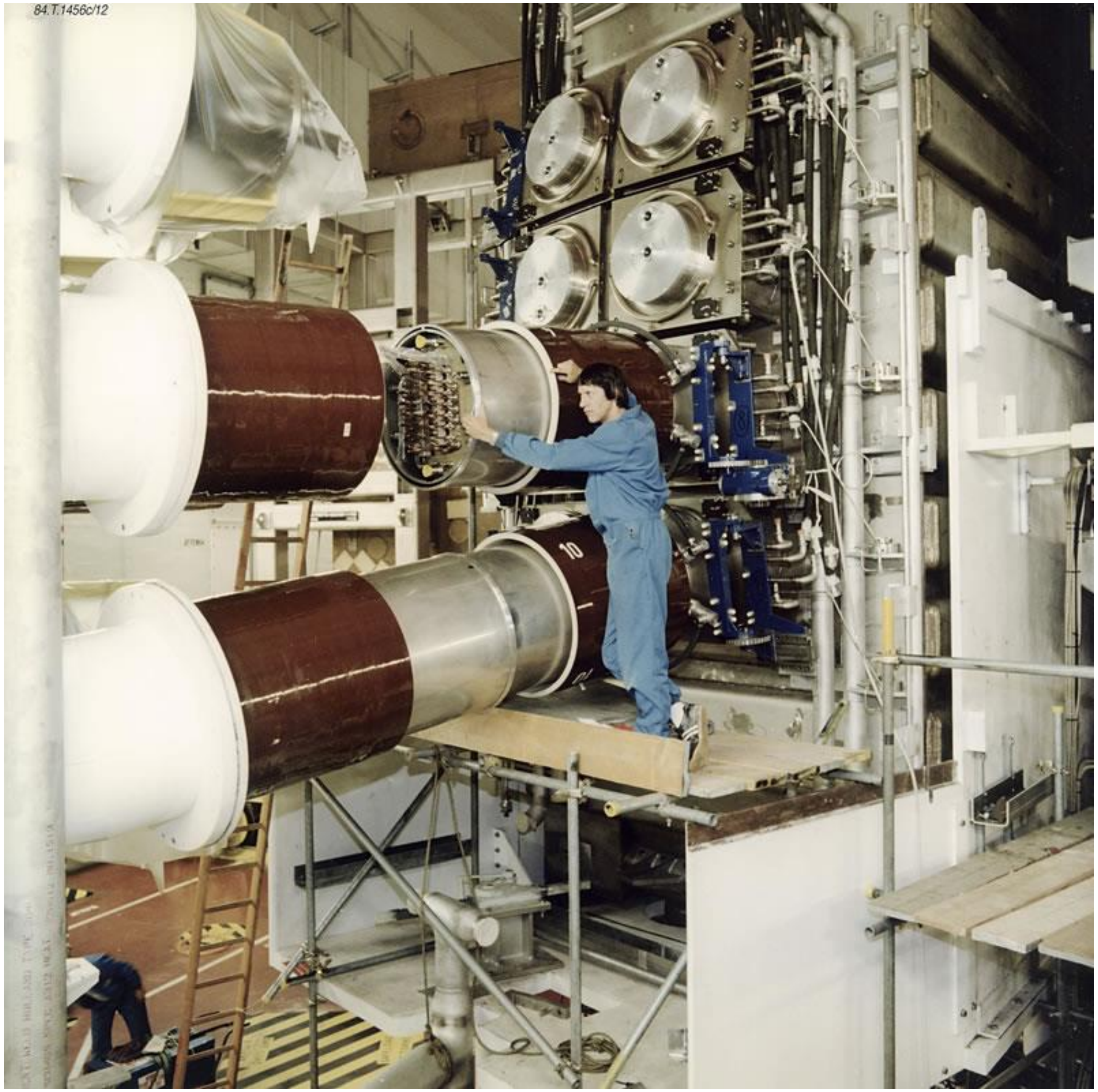
Fusion



JET Tokamak at
Culham, UK.

- Create plasma of D and T
- Heat it to 1×10^6 °C
- Compress it magnetic
- Cause fusion

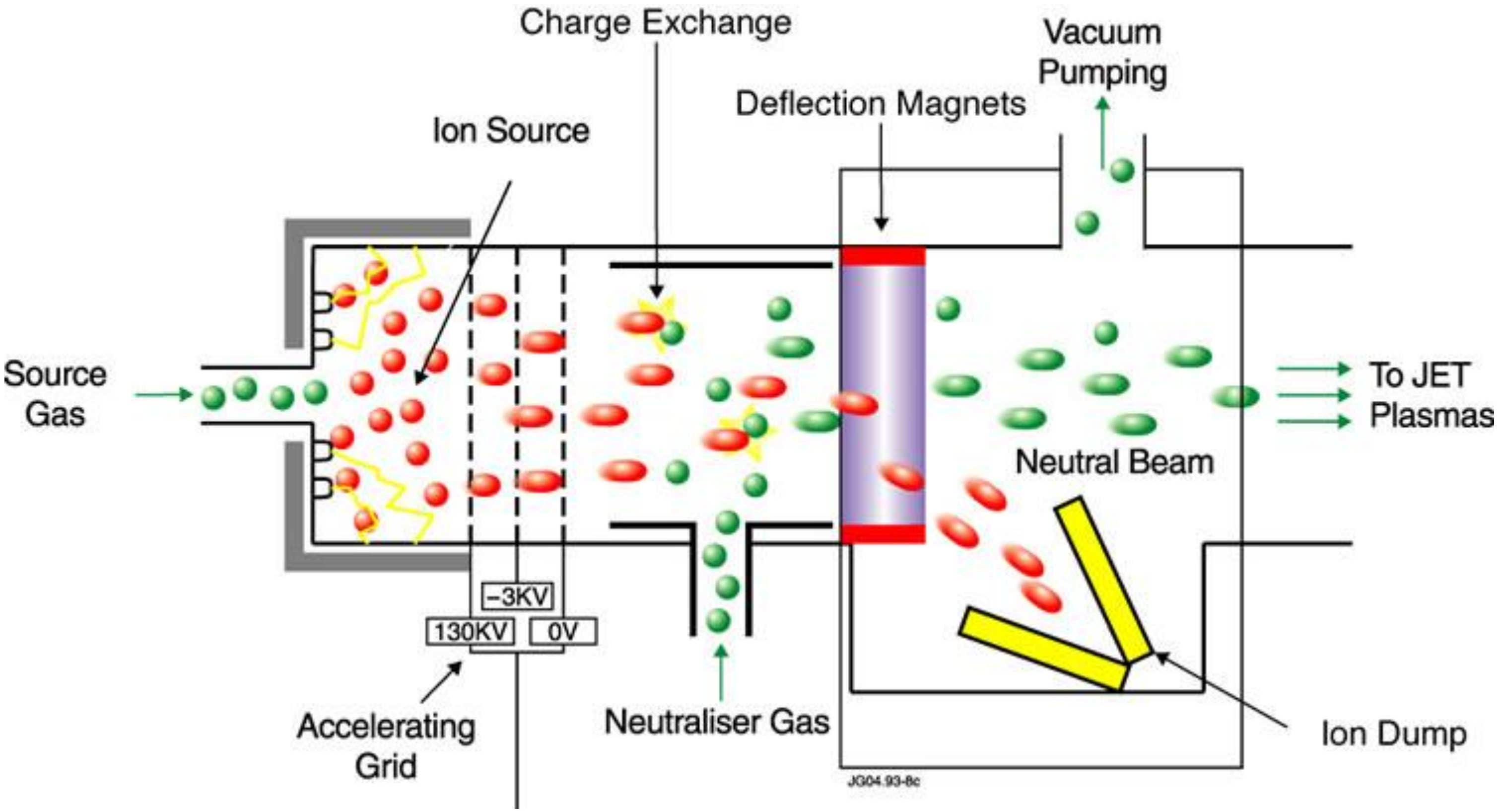
Fusion



JET Tokamak at
Culham, UK.

- Create plasma of D and T
- Heat it to 1x10^6 °C
- Compress it magnetic
- Cause fusion

Fusion



Neutral ions can produce 35 MW of heating for JET
Single biggest source

Fusion

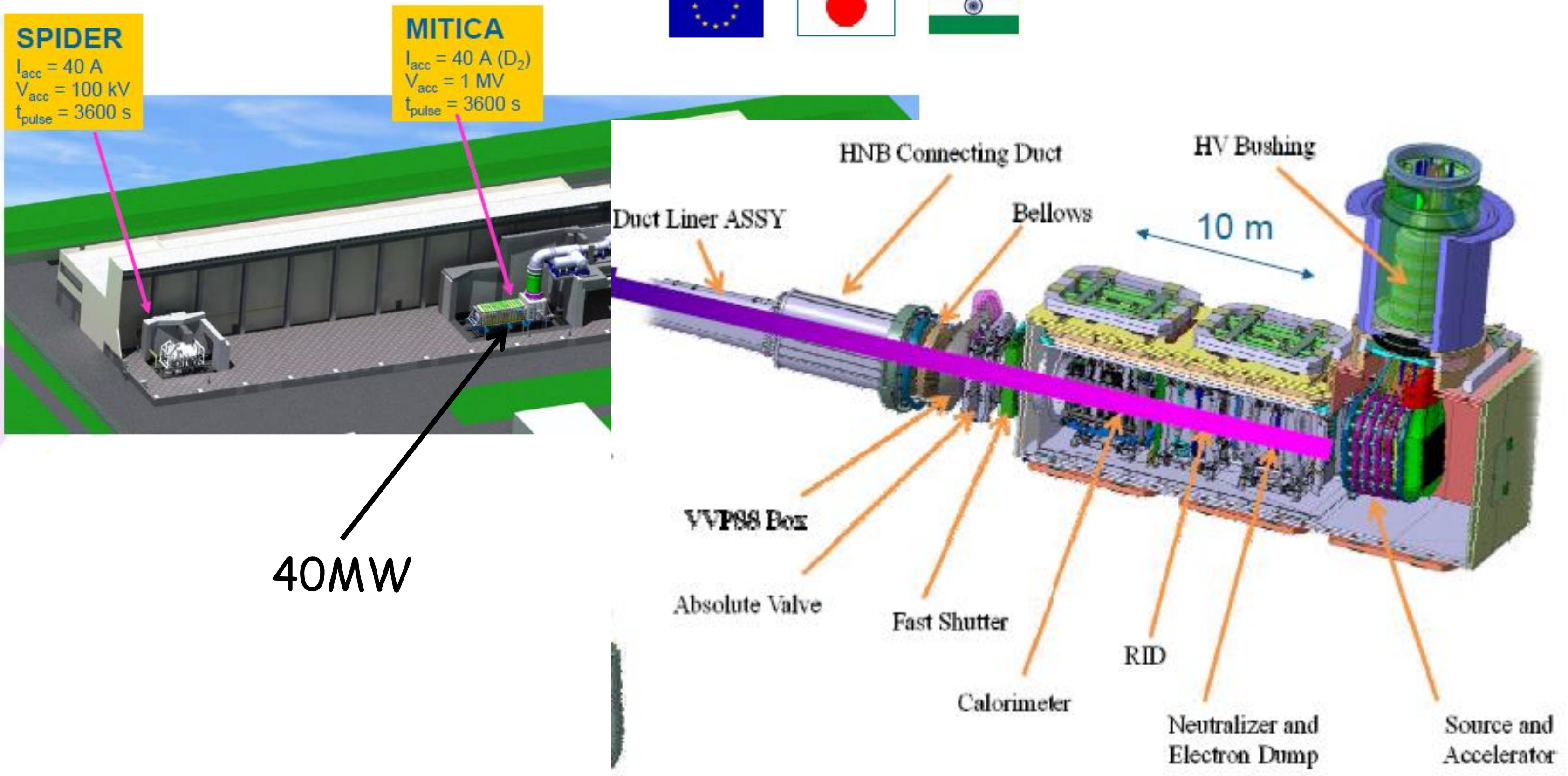
ITER Neutral Beam Test Facility (PRIMA)

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

iter
china eu india japan korea russia usa



SPIDER
I_{acc} = 40 A
V_{acc} = 100 kV
t_{pulse} = 3600 s

MITICA
I_{acc} = 40 A (D_2)
V_{acc} = 1 MV
t_{pulse} = 3600 s

40MW

Materials Research

Fusion:
Materials research

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

30 dpa/year

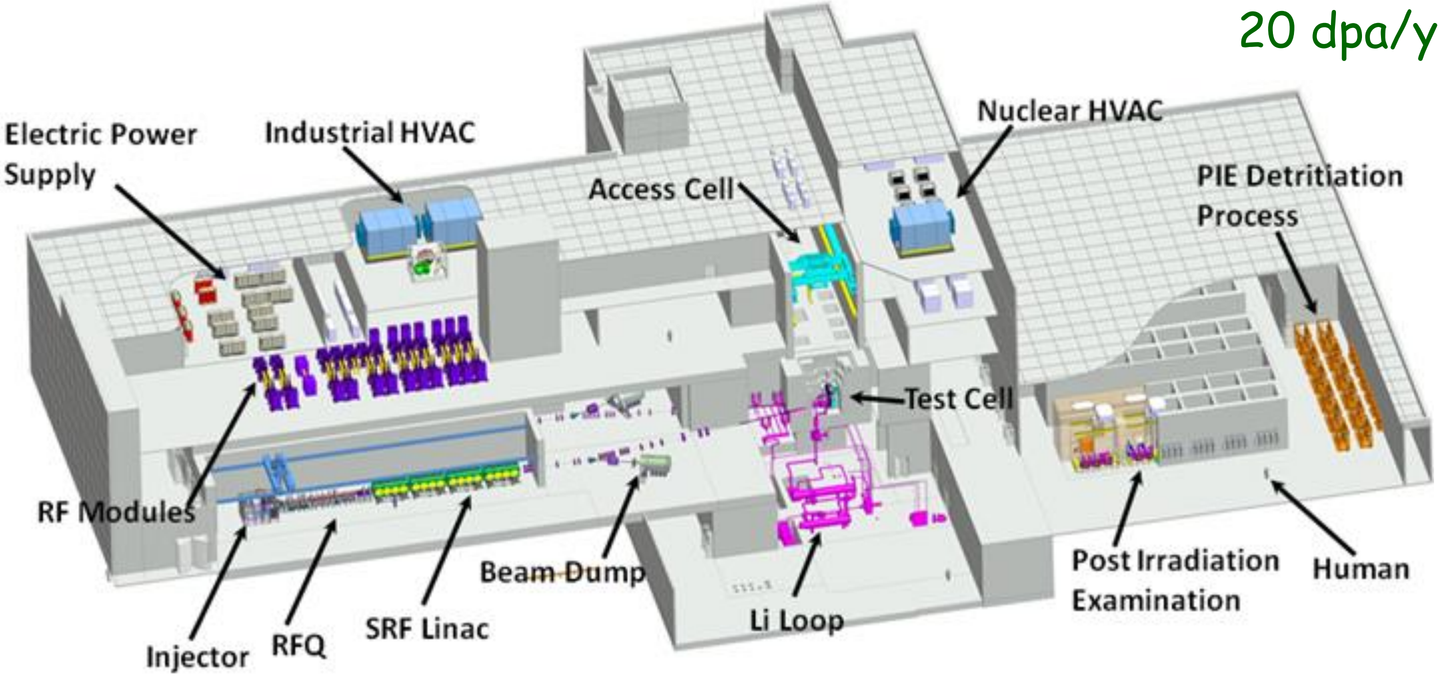
IFMIF:

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

2 x 40 MeV, 125 mA linear accelerators

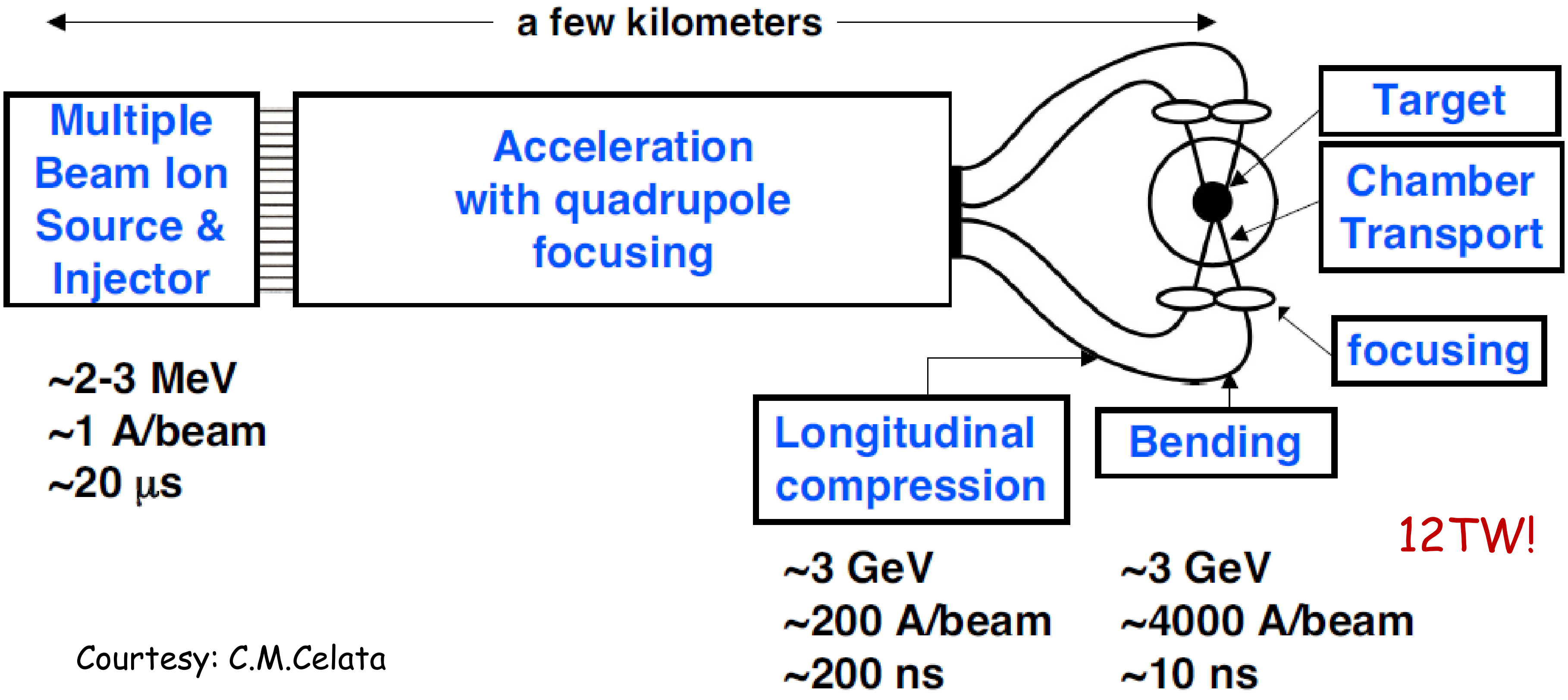
20 dpa/year

5MW/beam



Heavy Ion Inertial Fusion

- Use heavy ions to compress fuel for fusion
- Idea has been around since 1970s
- Being studied mainly in the US



a few kilometers

Multiple Beam Ion Source & Injector

Acceleration with quadrupole focusing

Target

Chamber Transport

focusing

Longitudinal compression

Bending

~2-3 MeV
~1 A/beam
~20 µs

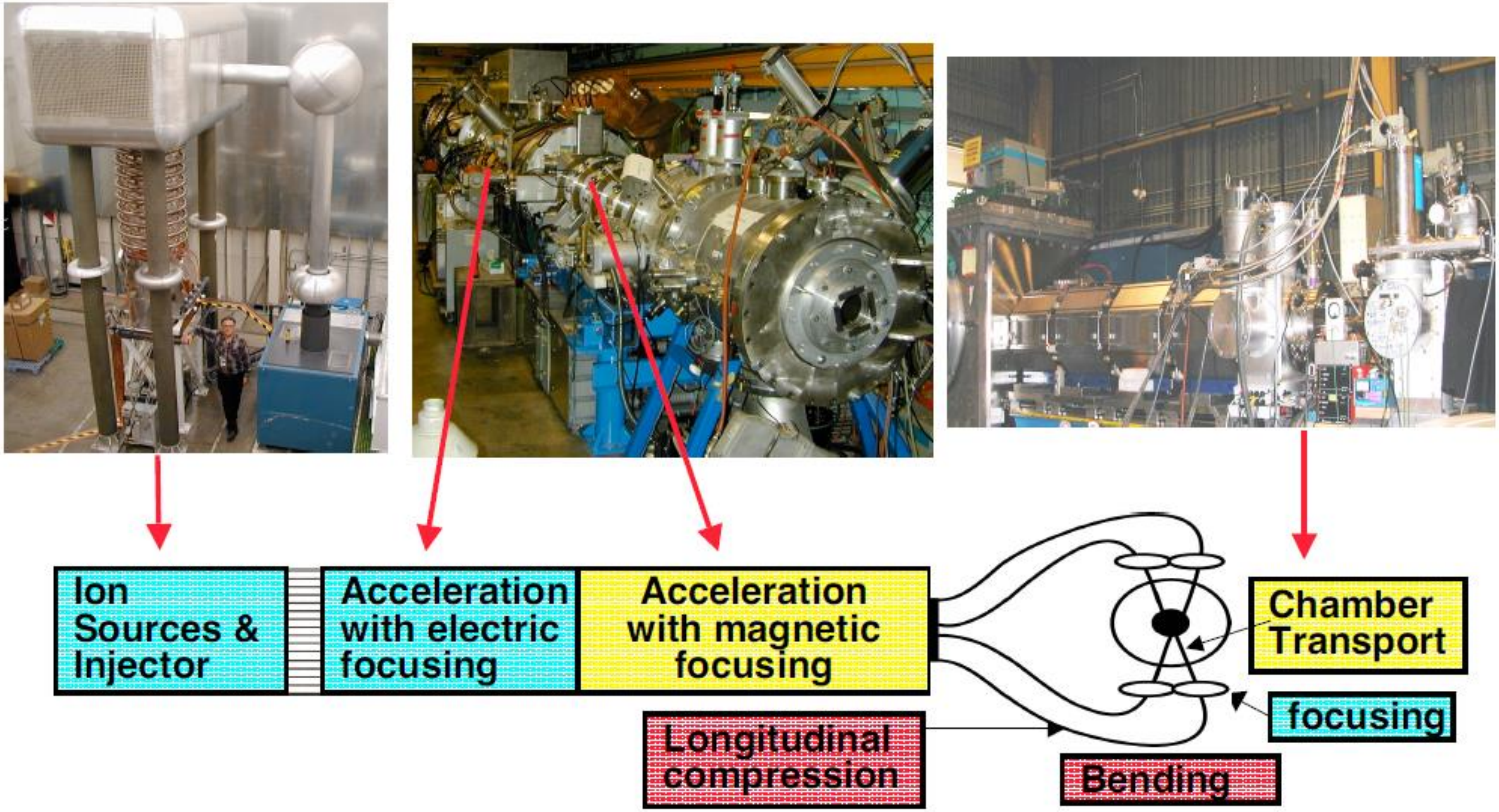
~3 GeV
~200 A/beam
~200 ns

~3 GeV
~4000 A/beam
~10 ns

12TW!

Courtesy: C.M.Celata

Heavy Ion Inertial Fusion



Ion Sources & Injector

Acceleration with electric focusing

Acceleration with magnetic focusing

Longitudinal compression

Bending

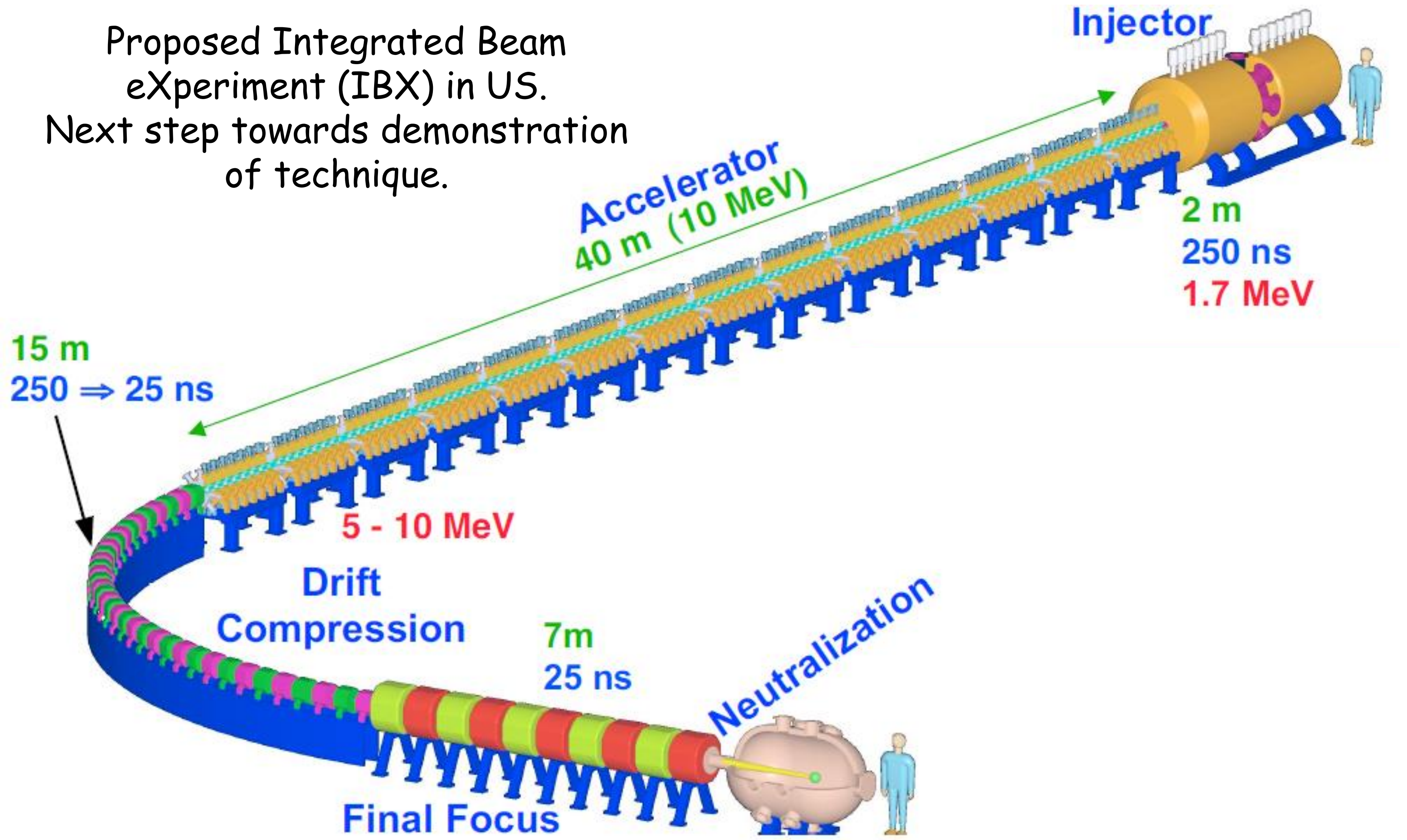
Chamber Transport

focusing

Courtesy: C.M.Celata

Heavy Ion Inertial Fusion

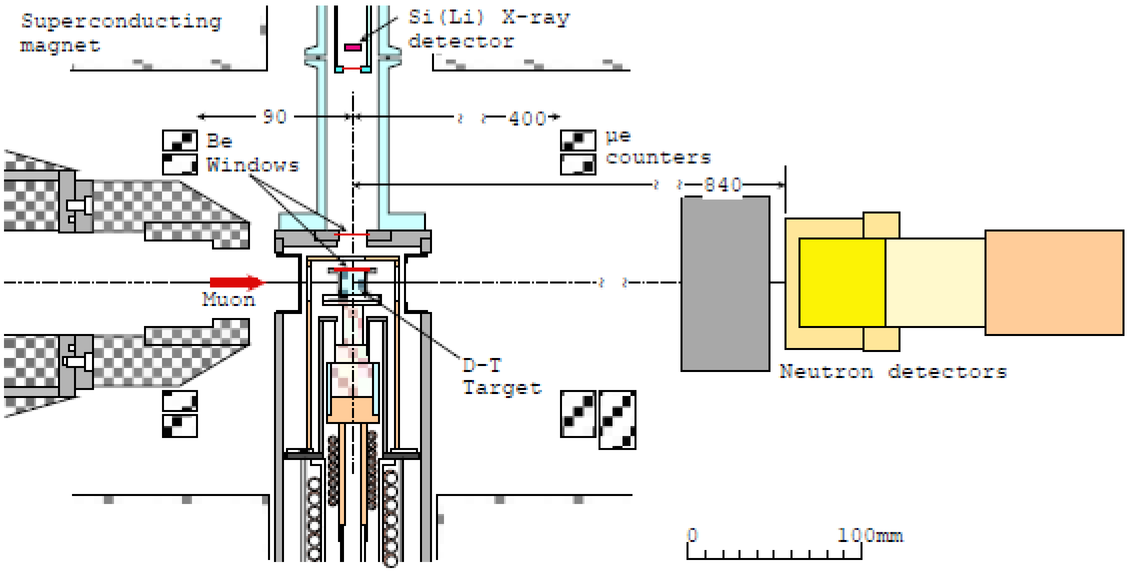
Proposed Integrated Beam eXperiment (IBX) in US.
Next step towards demonstration of technique.



Courtesy: C.M.Celata

Muon Catalysed Fusion

- Principle:
  - muonic atoms ~200 times smaller than standard
  - coulomb barrier thinner
  - fusion easier
  - muon released after fusion, hence catalyst
- Studied in various labs, e.g. Dubna, TRIUMF, PSI, KEK, RAL
- Works, but muons needs to be 10x cheaper



Energy Conclusions

- Accelerators being studied for fission and fusion use
- Still under development
- Pushing (or well beyond!) the boundaries:
  - beam current
  - beam power
- ADS linac studies have built on:
  - CERN work on Superconducting Proton Linac (SPL)
  - European Spallation Source