Maurizio Vretenar CERN

# LECTURE 7

RTU/CERN May 2022

# Applications of Accelerators

# Accelerators for Society

Over 35'000 particle accelerators are in operation world-wide.

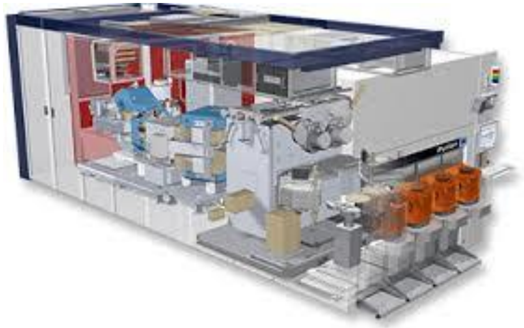
Only ~1% are used for fundamental research.

Medicine is the largest application with more than 1/3 of all accelerators.

| **Research** | | **6%** |
|---|---|---|
| | Particle Physics | 0,5% |
| | Nuclear Physics, solid state, materials | 0,2 - 0,9% |
| | Biology | 5% |
| **Medical Applications** | | **35%** |
| | Diagnostics/treatment with X-ray or electrons | 33% |
| | Radio-isotope production | 2% |
| | Proton or ion treatment | 0,1% |
| **Industrial Applications** | | **<60%** |
| | Ion implantation (semiconductors) | 34% |
| | Cutting and welding with electron beams | 16% |
| | Polymerization | 7% |
| | Neutron testing | 3.5% |
| | Non destructive testing | 2,3% |

*Radiotherapy electron linac*

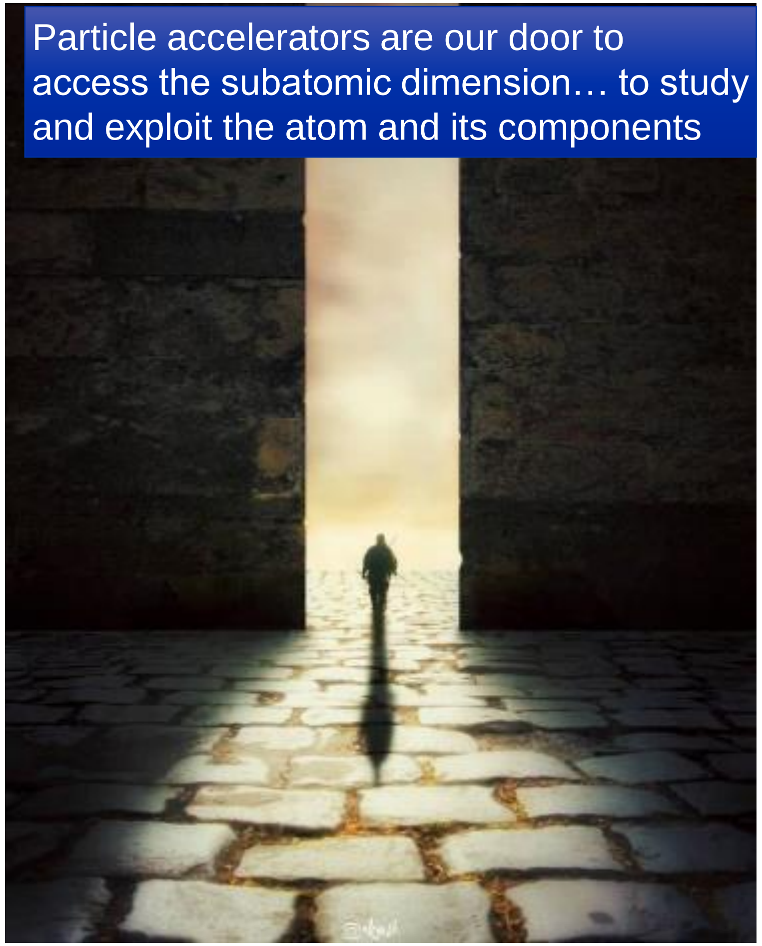
*Proton cyclotron for radioisotope production*



*Commercial system for ion implantation*

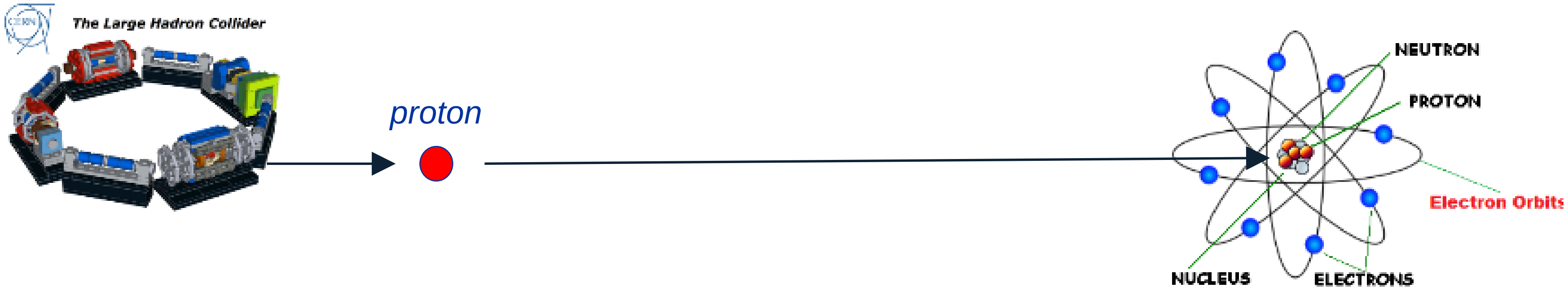
# Particle Accelerators can concentrate energy

A particle accelerator is an instrument capable of concentrating large amounts of energy at subatomic dimensions



Particle accelerators are our door to access the subatomic dimension… to study and exploit the atom and its components

When we extract particles from an atom and we accelerate them, we concentrate **enormous amounts of energy in tiny volumes**



Where will this energy go? An accelerated subatomic particle sent towards an atom will:

1. Deliver some **energy to the electrons**.
2. Deliver some **energy to the nucleus** (if the particle has sufficient energy to penetrate the atom.

# Where does the energy go?

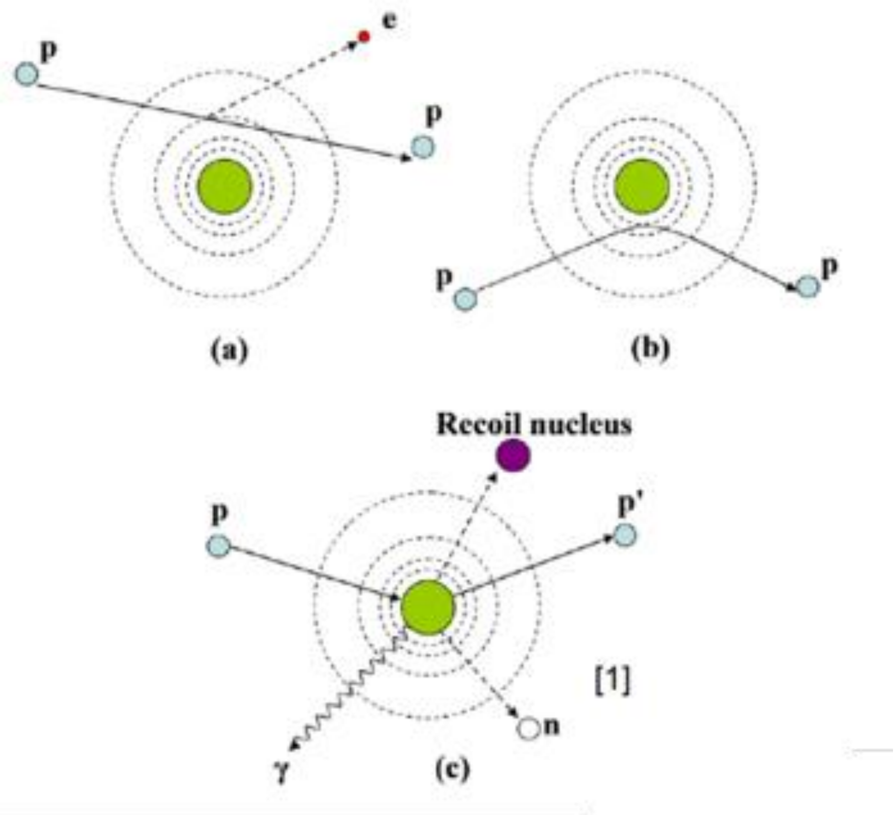
The accelerated particle can:

a) kick an electron out of the atom (ionization) or to a higher orbital (excitation) – in the latter case, the electron can come back generating an **X-ray** (photon).

b) be deflected by the nucleus and give energy to the atom - increase of temperature, **breaking of molecular bonds**.

c) be absorbed by the nucleus bringing it to an excited state that can **generate radiation** or secondary particles.

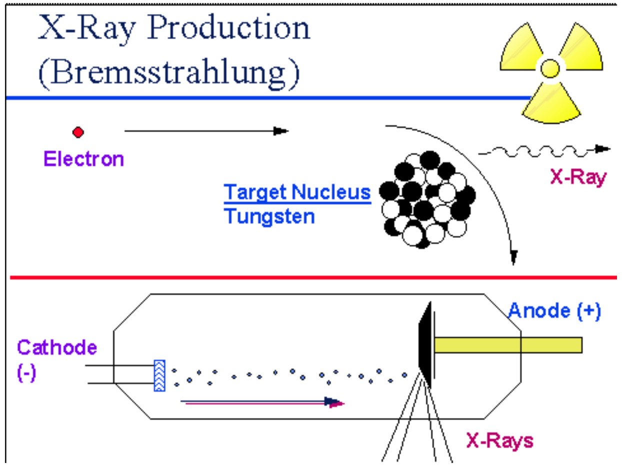
Scattering of an accelerated beam

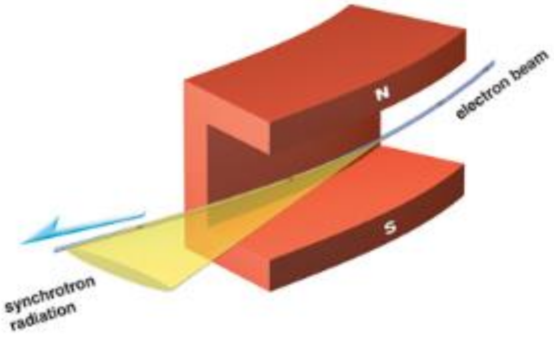


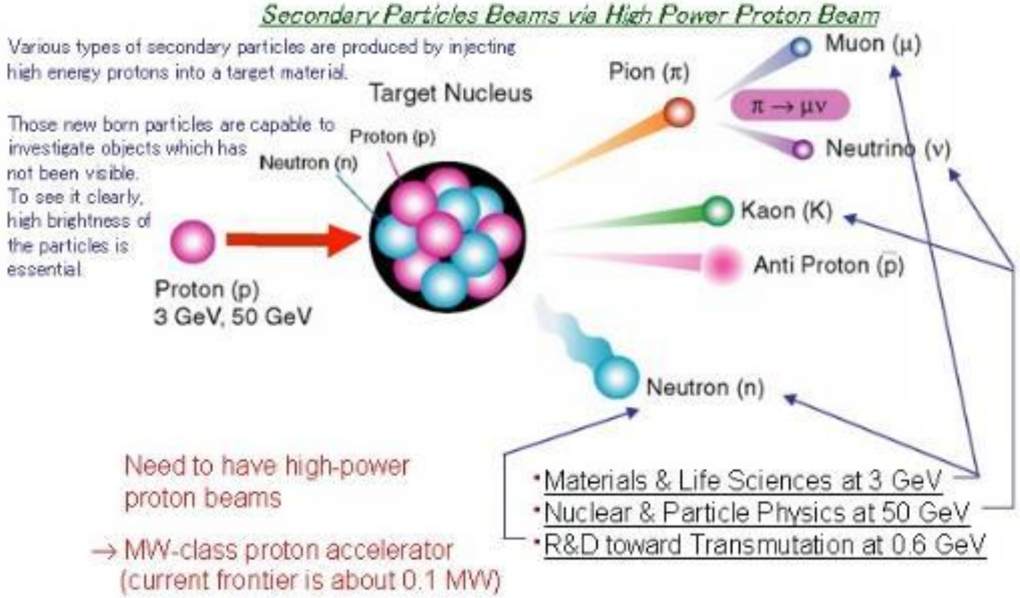
# Accelerators can produce intense secondary beams

Accelerated electrons produce X-ray beams by interaction with a metal target (bremsstrahlung) or by synchrotron radiation in accelerator magnets)

Accelerated protons produce neutron beams by spallation reactions in a heavy metal target







Various types of secondary particles are produced by injecting high energy protons into a target material.

Those new born particles are capable to investigate objects which has not been visible. To see it clearly, high brightness of the particles is essential.

Need to have high-power proton beams

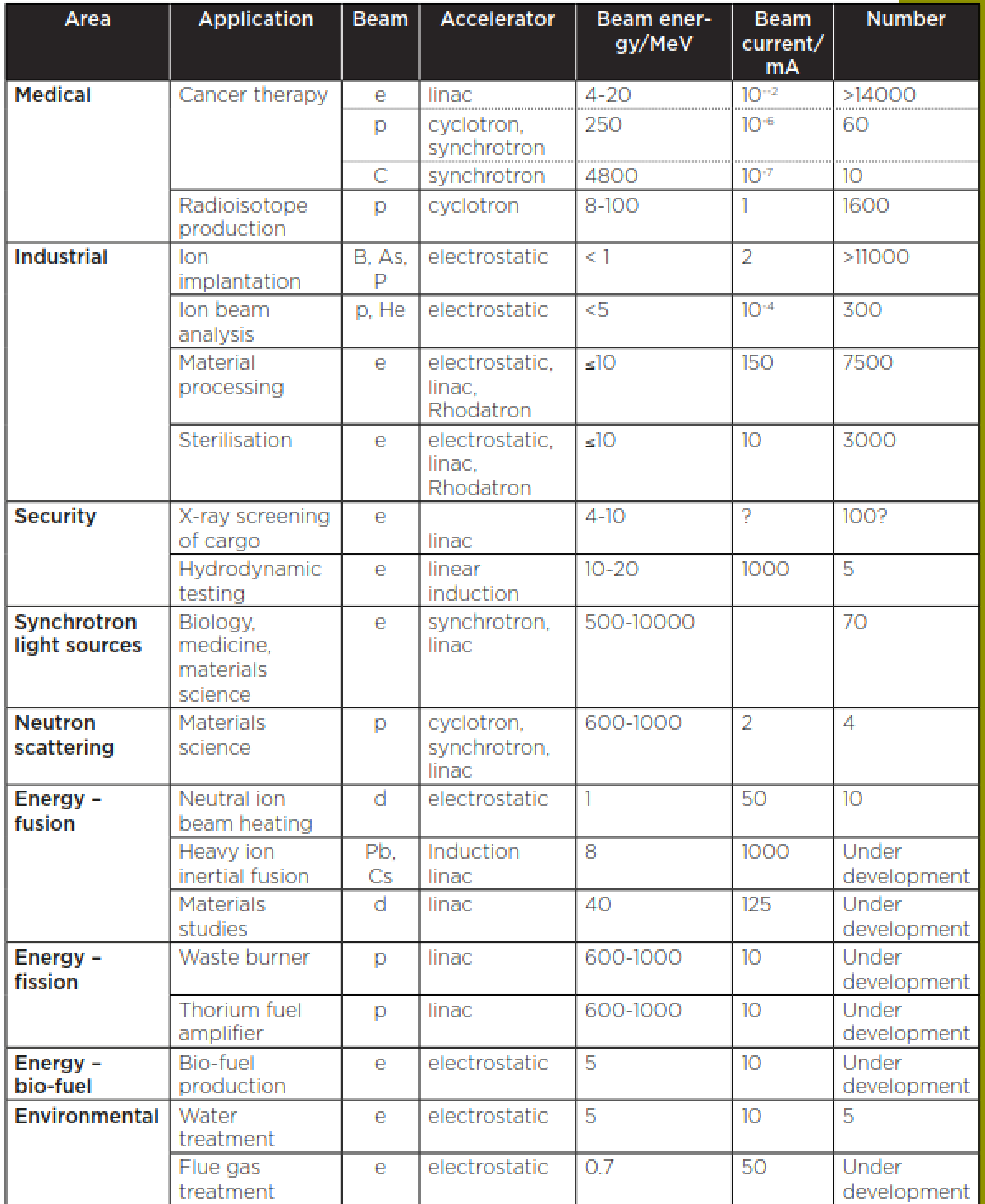
→ MW-class proton accelerator (current frontier is about 0.1 MW)

- Materials & Life Sciences at 3 GeV
- Nuclear & Particle Physics at 50 GeV
- R&D toward Transmutation at 0.6 GeV

- X-rays generated by accelerators are commonly used in **medicine**
- Both X-rays and neutrons generated from accelerators are used for **advanced imaging** in many fields: life sciences, condensed matter, energy, material science, cultural heritage, life sciences, pharmaceuticals,…
- Additional applications are appearing for other types of secondary beams.

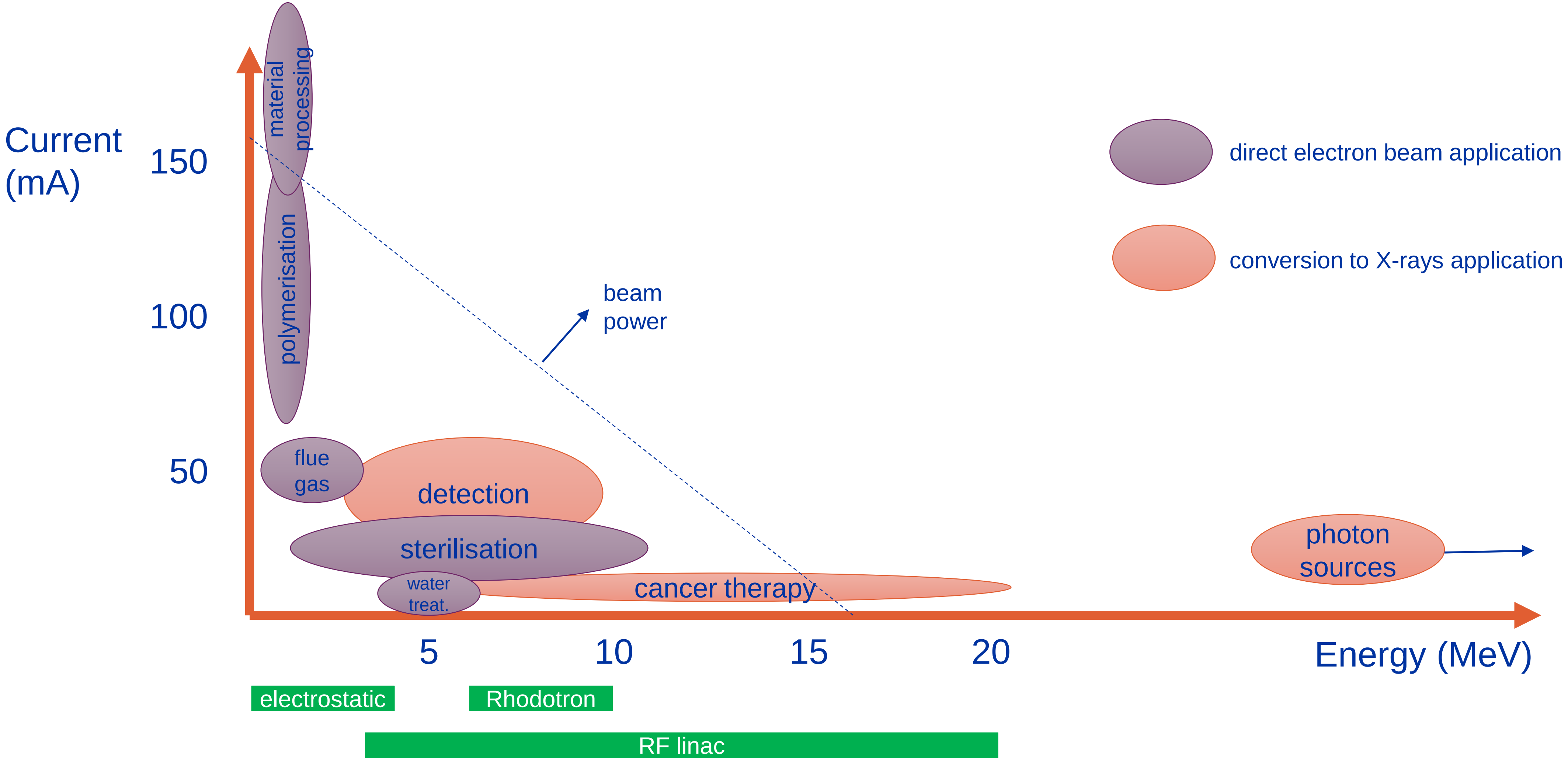
# An inventory of most popular accelerator applications

1. Photon and Neutron Sources
2. Security (X-rays, neutrons)
3. Industry
4. Energy
5. Medicine

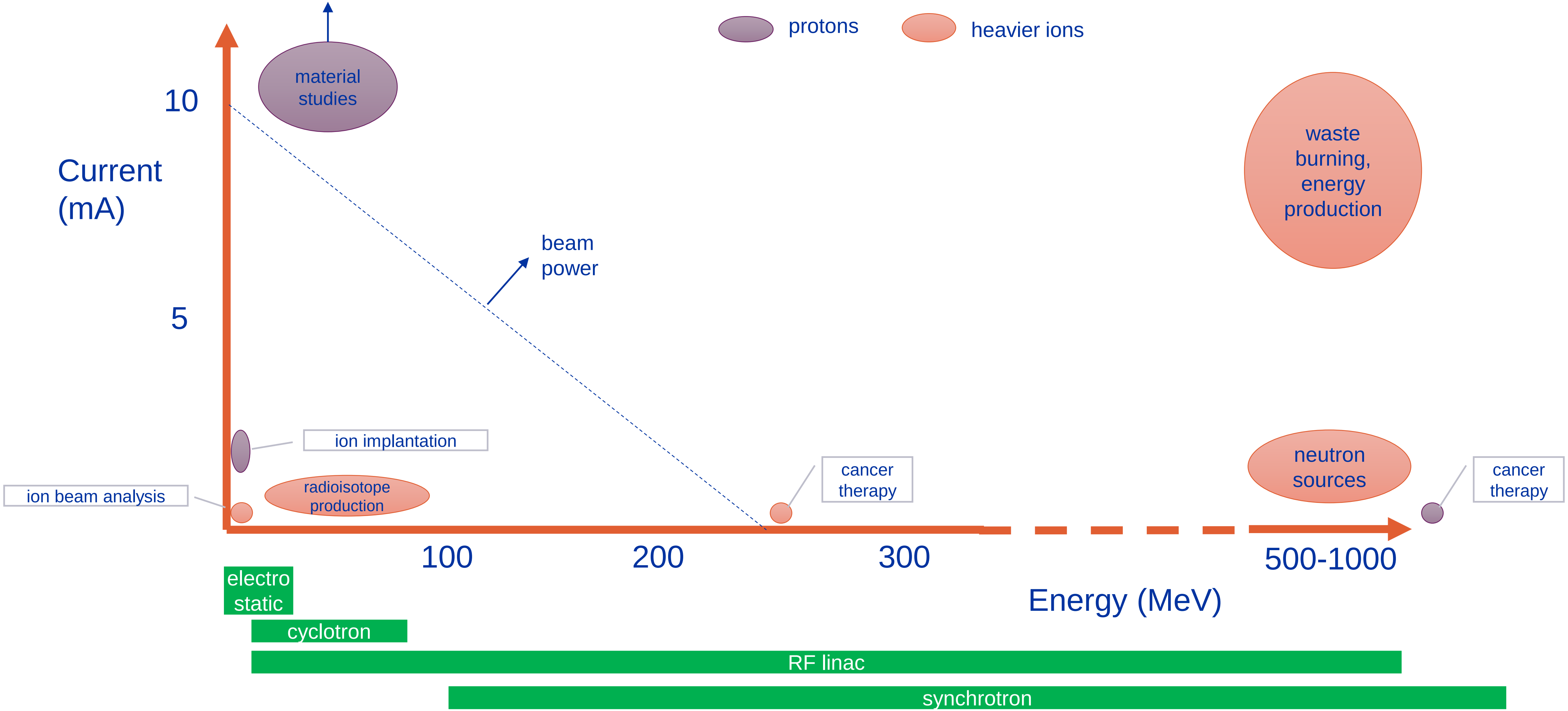


| Area | Application | Beam | Accelerator | Beam energy/MeV | Beam current/ mA | Number |
|---|---|---|---|---|---|---|
| **Medical** | Cancer therapy | e | linac | 4-20 | $10^{-2}$ | >14000 |
| | | p | cyclotron, synchrotron | 250 | $10^{-6}$ | 60 |
| | | C | synchrotron | 4800 | $10^{-7}$ | 10 |
| | Radioisotope production | p | cyclotron | 8-100 | 1 | 1600 |
| **Industrial** | Ion implantation | B, As, P | electrostatic | < 1 | 2 | >11000 |
| | Ion beam analysis | p, He | electrostatic | <5 | $10^{-4}$ | 300 |
| | Material processing | e | electrostatic, linac, Rhodatron | ≤10 | 150 | 7500 |
| | Sterilisation | e | electrostatic, linac, Rhodatron | ≤10 | 10 | 3000 |
| **Security** | X-ray screening of cargo | e | linac | 4-10 | ? | 100? |
| | Hydrodynamic testing | e | linear induction | 10-20 | 1000 | 5 |
| **Synchrotron light sources** | Biology, medicine, materials science | e | synchrotron, linac | 500-10000 | | 70 |
| **Neutron scattering** | Materials science | p | cyclotron, synchrotron, linac | 600-1000 | 2 | 4 |
| **Energy – fusion** | Neutral ion beam heating | d | electrostatic | 1 | 50 | 10 |
| | Heavy ion inertial fusion | Pb, Cs | Induction linac | 8 | 1000 | Under development |
| | Materials studies | d | linac | 40 | 125 | Under development |
| **Energy – fission** | Waste burner | p | linac | 600-1000 | 10 | Under development |
| | Thorium fuel amplifier | p | linac | 600-1000 | 10 | Under development |
| **Energy – bio-fuel** | Bio-fuel production | e | electrostatic | 5 | 10 | Under development |
| **Environmental** | Water treatment | e | electrostatic | 5 | 10 | 5 |
| | Flue gas treatment | e | electrostatic | 0.7 | 50 | Under development |

# The applications map - electrons



# The applications map – protons and ions



# Industrial applications

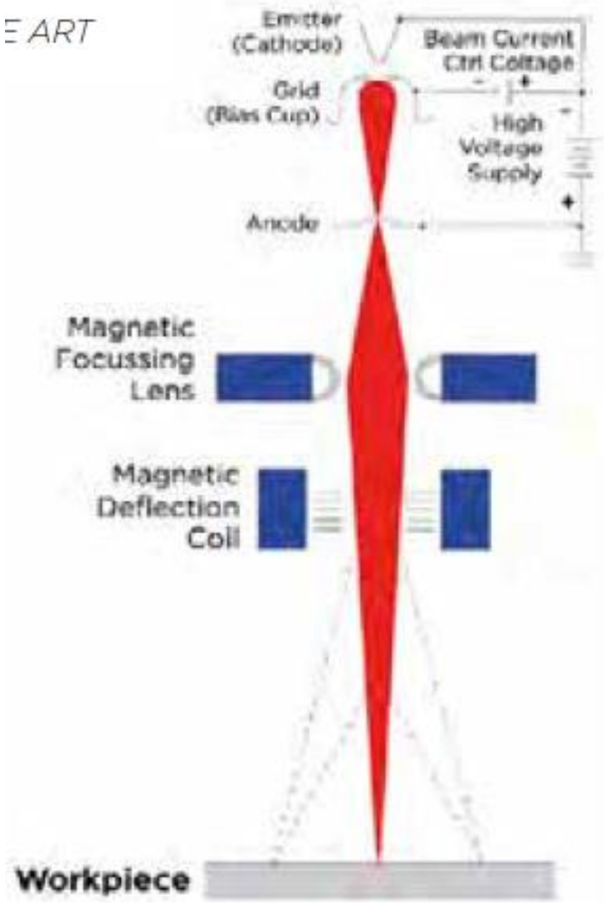
# Very low energy electrons

| | Energy | Applications |
|---|---|---|
| Very low energy electrons | <350 keV | detection, welding, 3D-sintering, sterilisation, seed and grain treatment |
| Low-energy electrons | <10 MeV | polymer modification, sterilisation, treatment of flue-gas, wastewater, sewage |

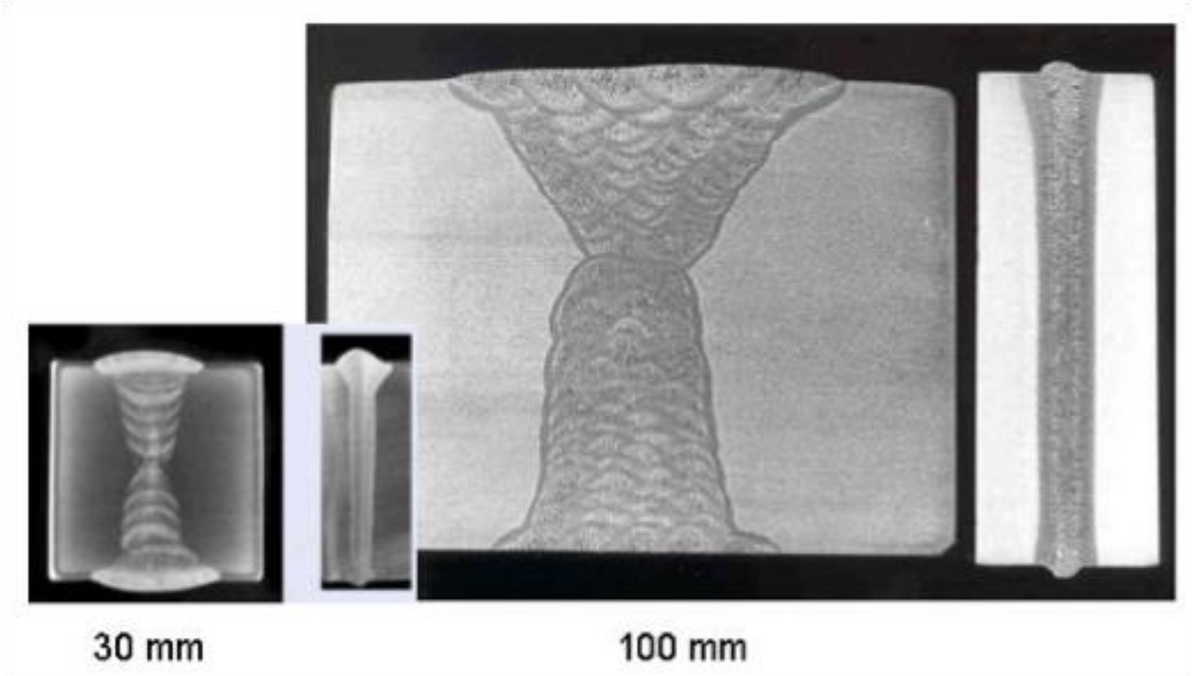
- ➢ Non-thermal: breaking molecular bonds, chemical modifications of organic materials, creation of radicals.
- ➢ Thermal: melting, evaporation, welding, joining, drilling, hardening, sintering,…

*Fig. 4.7: An impressive example of an EB-welding application. In a huge vacuum chamber two 70-mm-thick aluminium plates, with a diameter of 6 metres, are joined with a 'single-shot'. It is the basic material used in forging and machining the main stage of Ariane-rocket tanks.*

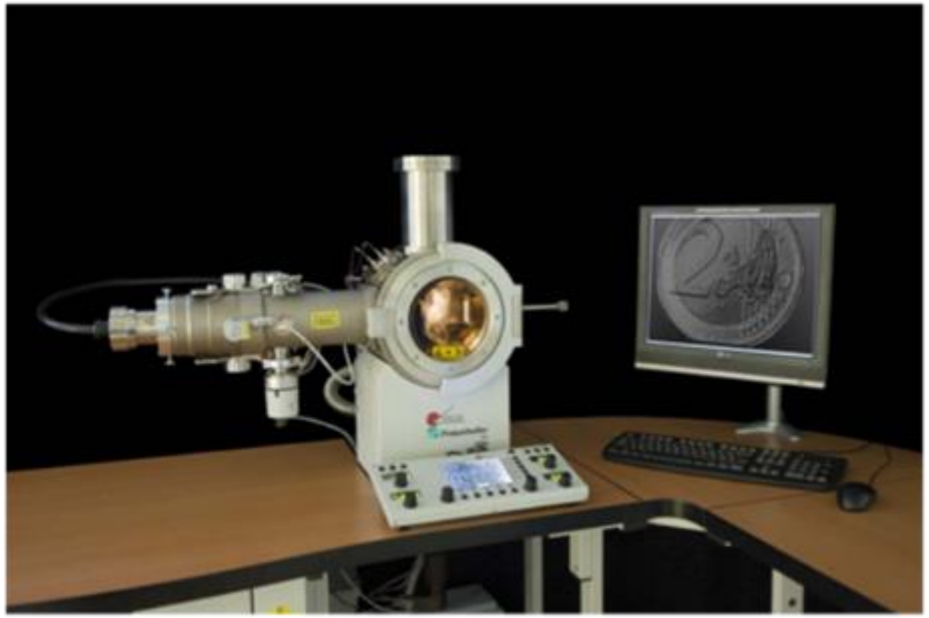
*Fig. 4.8: A desk-top e-beam laboratory machine for welding and structuring with a magnified backscattered electron-image.*



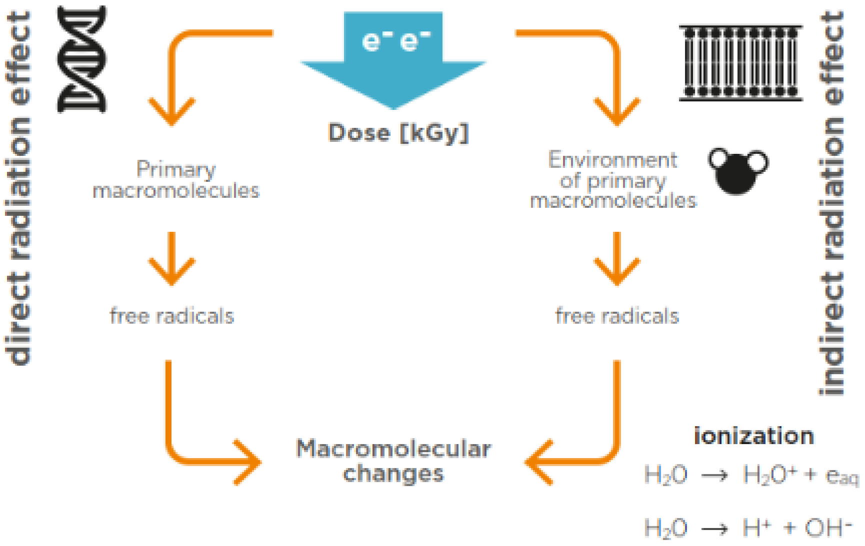
# Electron beam welding



Cross-sections - Comparison of extensive TIG-welding with a lot of weld seams with the single-weld seam of EB-welding at the same material thickness



# Sterilisation



- DNA Line-break (single, double)
- Change or damage of bases
- Denaturation
- Cross linking
- Absorption of proteins

*Fig. 4.2: Biocidal effects of accelerated electrons*

- Sterilisation processes caused by the breaking of molecular bonds associated with the water and DNA in microbial cells.
- Medical products (implants and instruments), food, and pharmaceutical packaging can be sterilised.
- Energy between 1 and 10 MeV, all surfaces must be accessible (small penetration depth).
- The world market-leader in the aseptic carton packaging of liquid foods is currently undergoing the installation of e-beam sterilisation machines in the majority of its production facilities.

*Fig. 4.12: E-beam technology fo sterilising medical products*

*Fig. 4.13: Tetra Pak has a new generation of automated filling machines that uses e-beams to sterilise packaging.*

# Food sterilisation and radiophobia

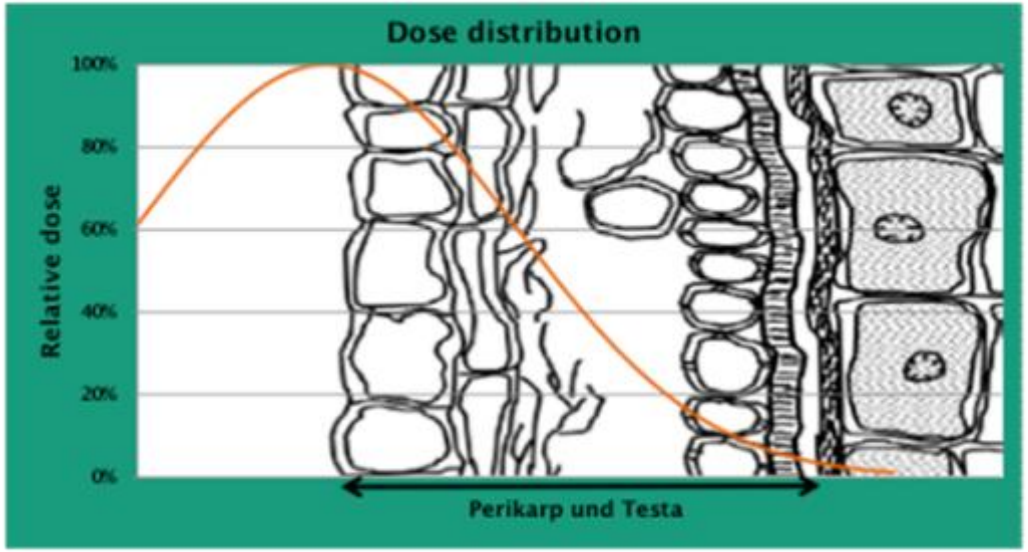
**Seed and crop treatment –** *20 to 30% of food harvested is lost to rotting and insect infestation*
Crop seeds must be free from pathogens (fungi, bacteria and viruses) that can endanger health and food security. Standard treatment: chemical seed dressing that can result in the contamination of soil and ground water with waste products, drifting of dressing agents across fields, killing of probiotic microorganisms.

Alternative: physical disinfection of seed using the **biocidal effect of accelerated electrons**. By precisely adjusting the energy of the e-beam, contamination on the seed surface can be treated without damaging the DNA of the seed grain.

**Advantages**:
- no change in taste, texture of colour;
- no toxic residue;
- less energy consumption than e.g. steaming;

E-beam treatment diffusion is limited by **low social acceptance** of any association between "radiation" and "food", which results as well in stringent regulatory constraints.

Crop treatment companies never use the word "radiation"…



# Environmental applications of low-energy electrons

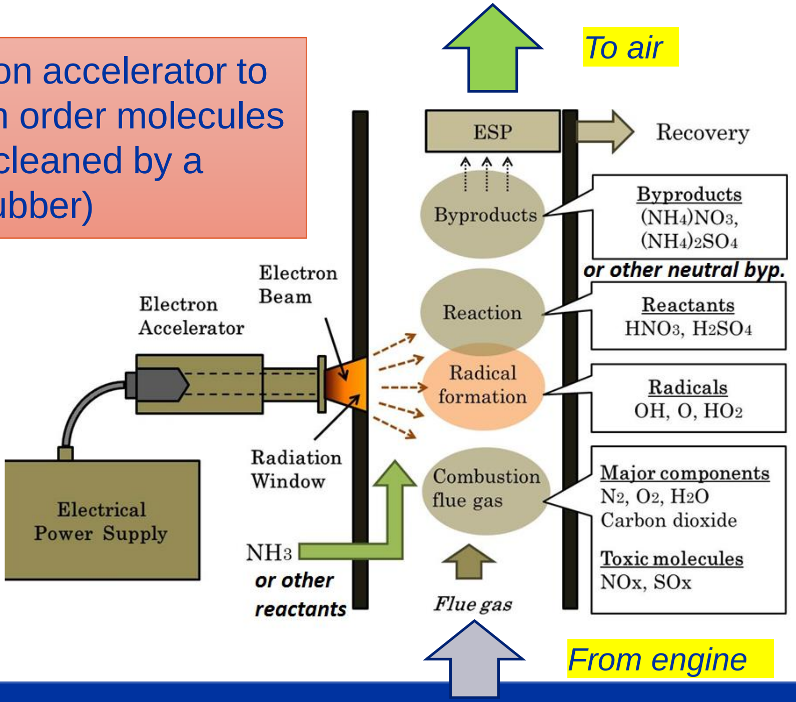
Low-energy electrons can break molecular bonds and be used for:
- Flue gas treatment (cleaning of SOx from smokes of fossil fuel power plants)
- Wastewater and sewage treatment
- Treatment of marine diesel exhaust gases (removal of SOx and NOx).

- **Maritime transport** is the largest contributor to air pollution: a cruise ship emits as much sulphur oxides as 1 million cars!
- Ships burn Heavy Fuel Oil, cheap but rich in Sulphur. Diesels (high efficiency) emit Nitrogen oxides and particulate matter.
- New legislation is going to drastically limit SOx and NOx emissions from shipping, with priority to critical coastal areas.
- So far, technical solutions exist to reduce SOx or NOx, but there is no economically viable solution for both.

**Hybrid Exhaust Gas Cleaning Retrofit Technology for International Shipping (HERTIS)**

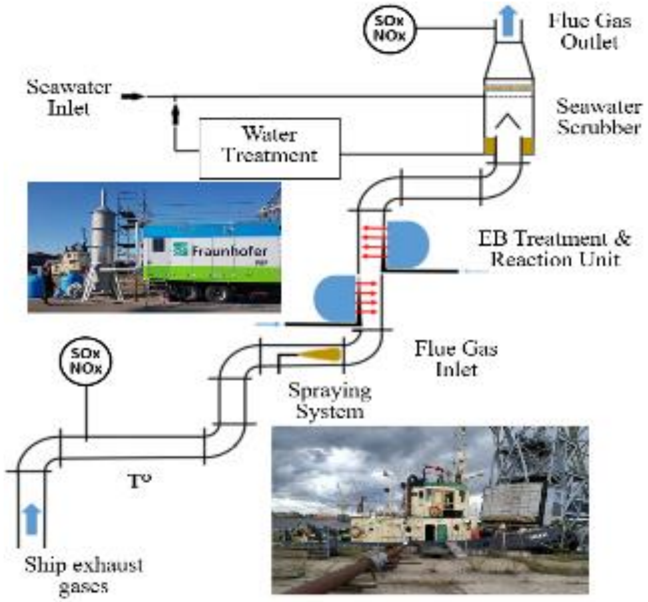
A project based on a patent from INCT Warsaw promoted by a collaboration of research institutions (including CERN), accelerator industry, shipyards, maritime companies, maritime associations (Germany, UK, Switzerland, Poland, Latvia, Italy).

150 kV electron accelerator to break the high order molecules that are then cleaned by a water jet (scrubber)



# Test of HERTIS at Riga Shipyard, July 2019

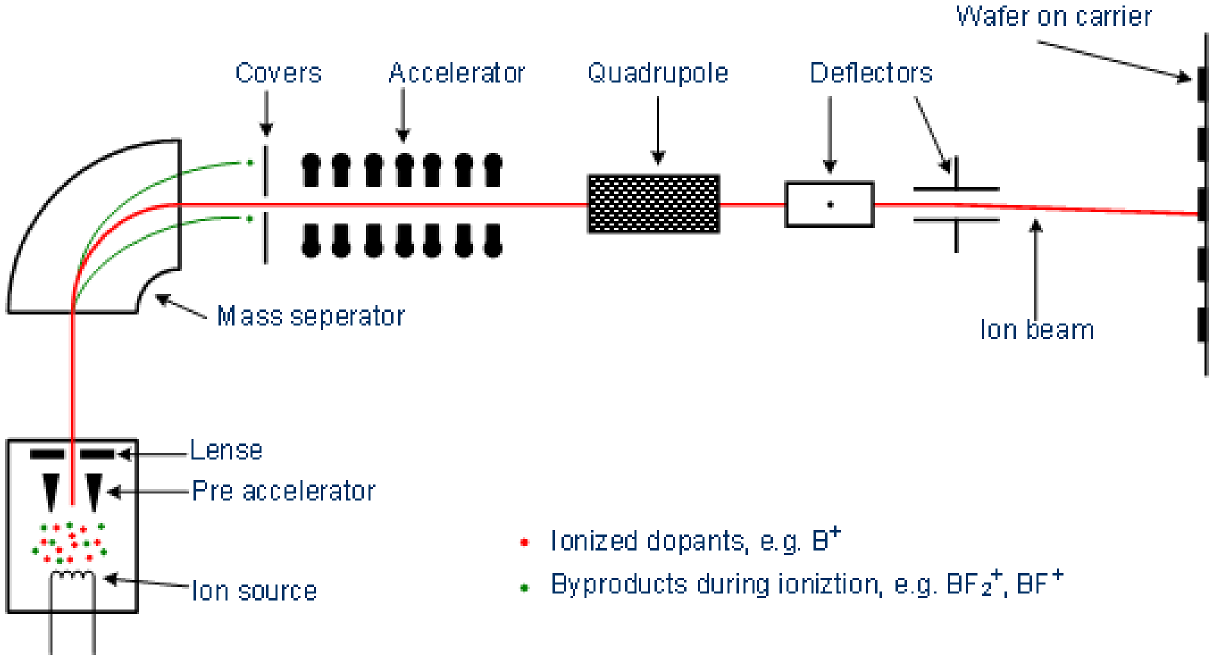
Mobile electron accelerator system from FAP Dresden commonly used to treat crops connected to the exhaust funnel of the Orkāns, an old Soviet-built tugboat. The fumes then passed through a small water scrubber before being released in the air.



The tests confirmed the laboratory measurements and the overall effectiveness of the system.

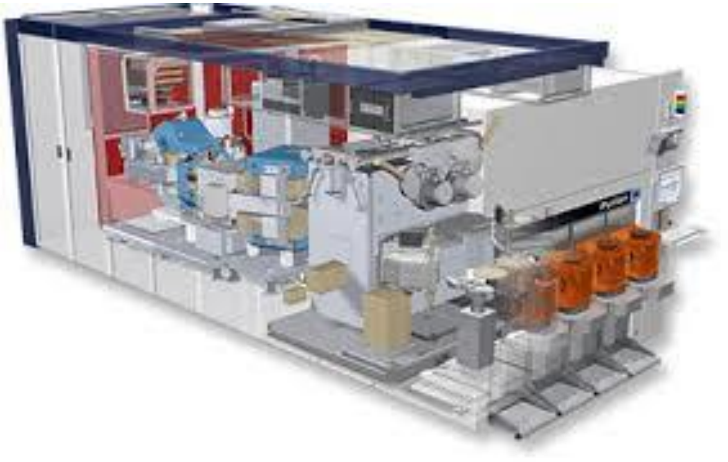
Measured **NOx removal rate 45%** at full engine power with the available scrubber and accelerator.
Estimated removal with optimised scrubber and homogeneous e-beam 98%.
SOx removal only measured in laboratory (no Sulphur allowed in port) with similar removal rates.

# Ion implantation

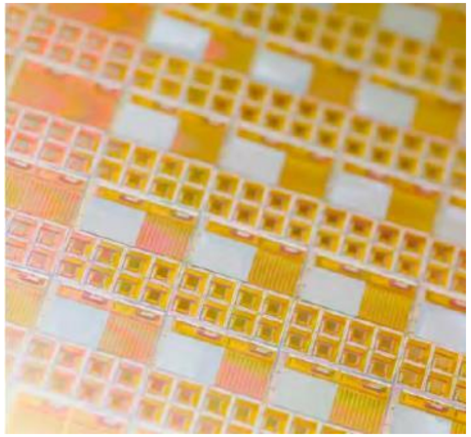


The **semiconductor industry** requires ion implantation to introduce atoms into semiconducting materials to alter their electronic properties (doping).
Huge industry and one of the most important uses of particle accelerators.

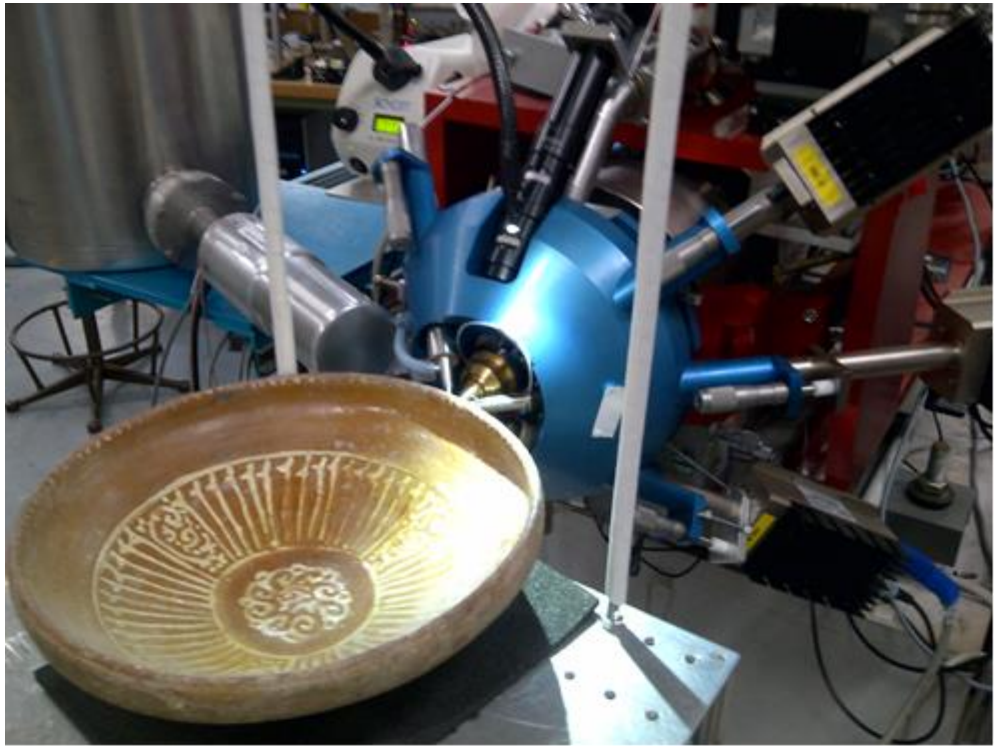
Developing into research for quantum computing (single ions with nanometre-scale spatial accuracy) and novel opto-electronic devices (nano-precipitates in silicon-dioxide layers for light-emitting devices).



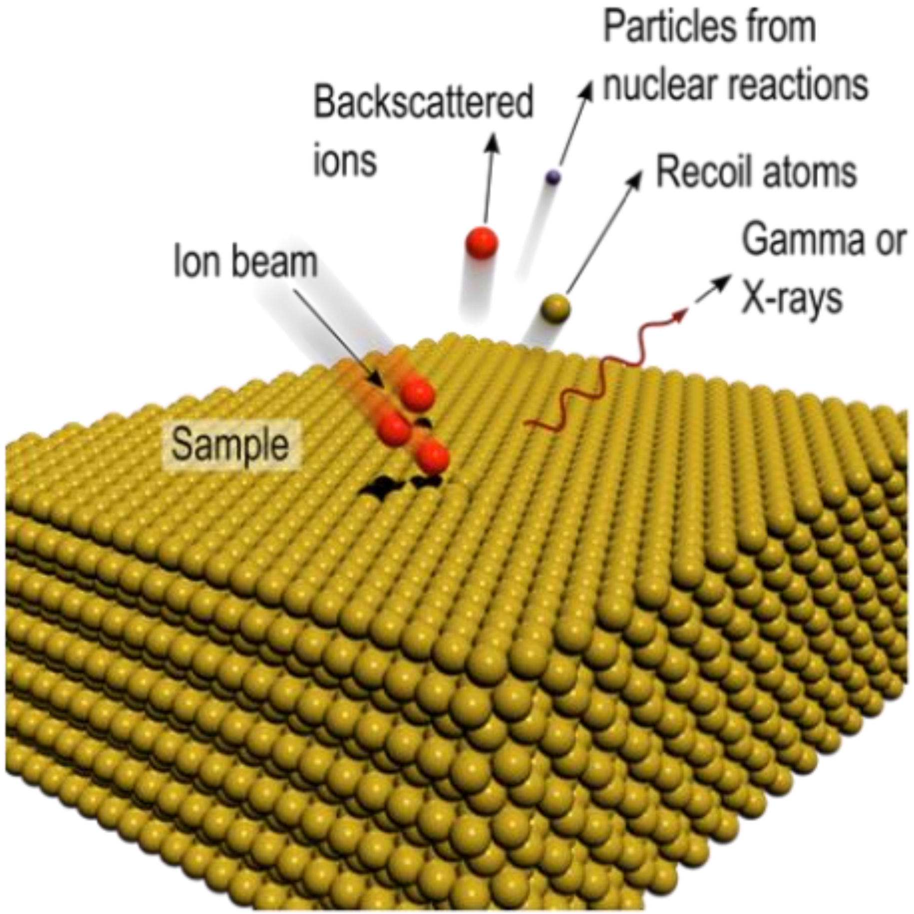
*Commercial system for ion implantation*



# Surface analysis applications



# Ion Beam Analysis



Analytical techniques that exploits the interactions of MeV protons or heavier ions with matter in order to determine the elemental composition and structure of the surface regions of solids (to depths of about 100 μm), from measured quantities such as the characteristic spectra of the resulting X-rays, gamma-rays or charged particles emitted.

- Elastic or Rutherford backscattering (EBS or RBS), with a particle detector at a backscattering angle;
- Particle-induced X-ray emission (PIXE), with an X-ray detector;
- Particle-induced gamma-ray emission (PIGE), with a gamma detector;
- Elastic recoil detection analysis (ERDA) with a particle detector at a forward recoil/scattering angle.

# Accelerators for art

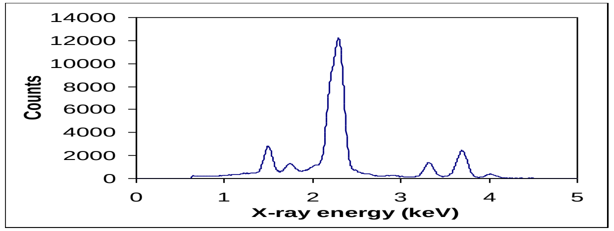
## PIXE, Proton Induced X-ray Emission

**A beam of particles (protons) from an accelerator is sent on a sample** (e.g. a painting)

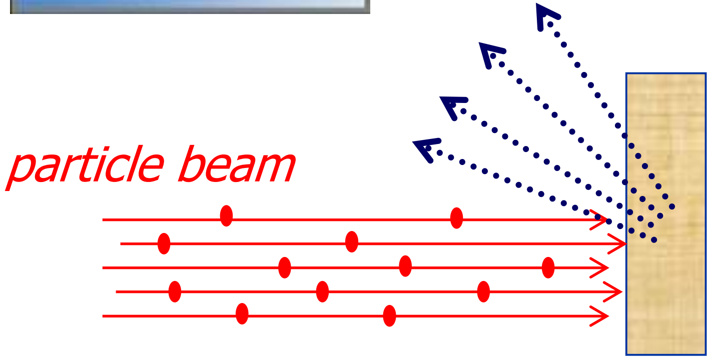
The atoms are excited and emit different types of radiation (X-rays, gammas, etc.)

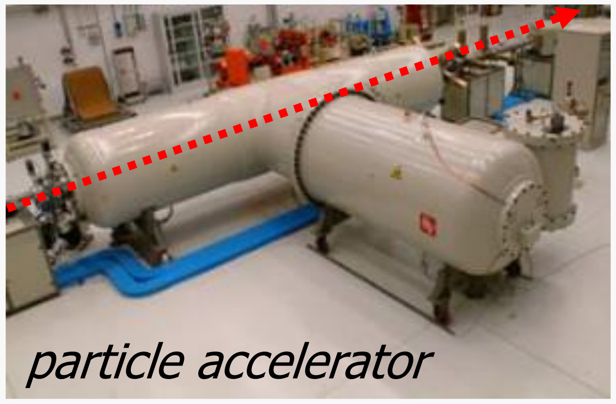
Different atomic elements emit X-rays at different energies – Spectral analysis from one or more detectors allows determination of the chemical composition (e.g. of the pigments).

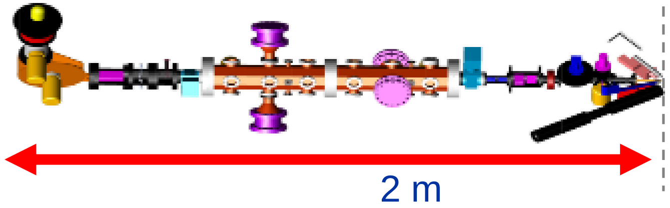
*Radiation detection and spectral analysis*



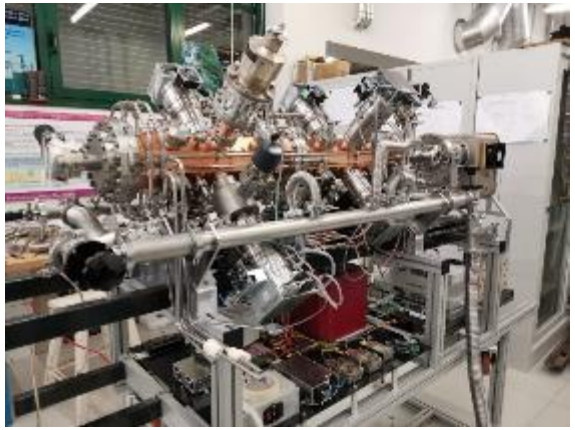
*Emission of radiation of characteristic energies* (X-rays, $\gamma$, particles…)





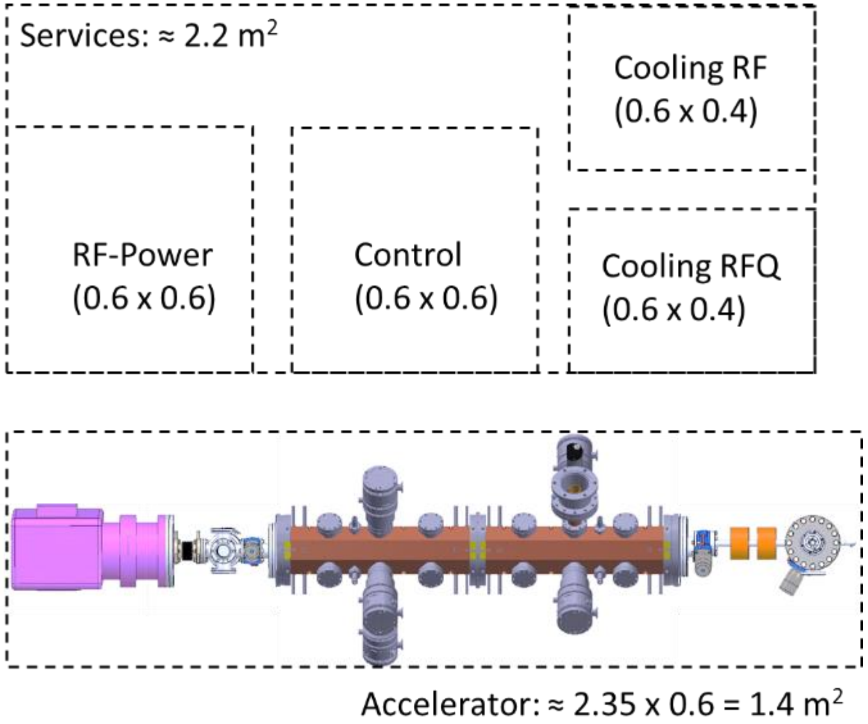


Ritratto Trivulzio by Antonello da Messina, 1476 – analysis at INFN-LABEC (Florence)



Portable PIXE system based on an RFQ linac being built by CERN and LABEC

# The MACHINA project



Services: ≈ 2.2 m$^2$

Cooling RF (0.6 x 0.4)

RF-Power (0.6 x 0.6)

Control (0.6 x 0.6)

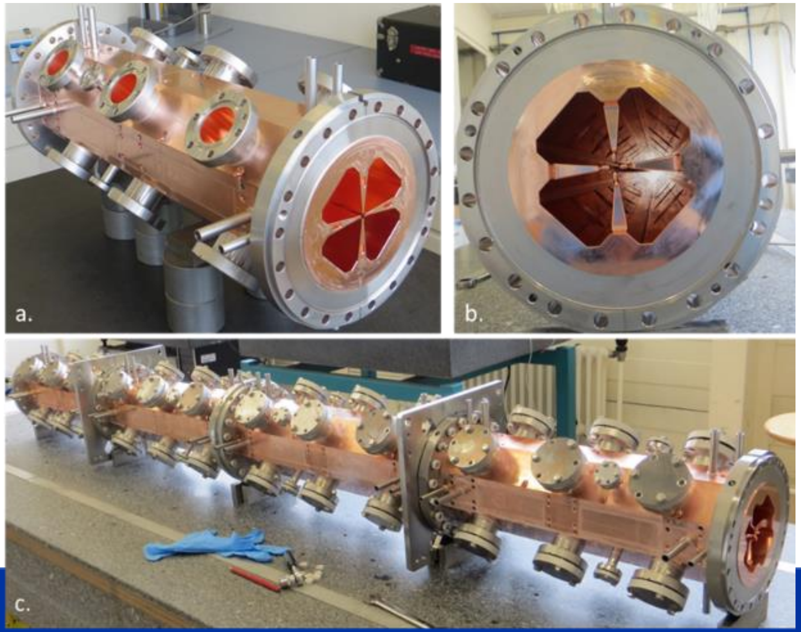
Cooling RFQ (0.6 x 0.4)

Accelerator: ≈ 2.35 x 0.6 = 1.4 m$^2$

MACHINA (Movable Accelerator for Cultural Heritage In situ Analysis) project of CERN and INFN.

Construction of a transportable RFQ (PIXE-RFQ) optimized for the analysis of material with a 2 MeV proton beam.

Will be installed in the Opificio delle Pietre Dure in Florence (Italian central institution for artwork analysis)



| | |
|---|---|
| RF Frequency (MHz) | 749.48 |
| Length (mm) | 1072.938 |
| Input Energy (MeV) | 0.02 |
| Output Energy (MeV) | 2 |
| Average Current (nA) | 5 |
| Peak Current (nA) | 200 |
| Repetion Rate (Hz) | 200 |
| Pulse Duration (ms) | 0.125 |
| Duty Cycle (%) | 2.5 |
| Vane Voltage (kV) | 35 |
| Min Aperture (mm) | 0.7 |
| Max Modulation | 2 |
| Ro (mm) | 1.439 |
| Rho (mm) | 1.439 |
| Rhol min (mm) | 1.709 |
| Transmission (%) (for matched beam) | 30 |
| Output Beam diameter (mm) | 0.5 |
| Acceptance (π mrad mm) (Total norm.) | 0.2 |
| Output Energy Spread (keV) | 10 |
| RF Peak Power (kW) | 80 |
| RF Average Power (kW) | 2 |
| RF Efficiency (%) | 35 |
| Coupler (#) | 1 |
| Plug Power (Total) (KVA) | 5.7 |

# Towards the miniature accelerator?

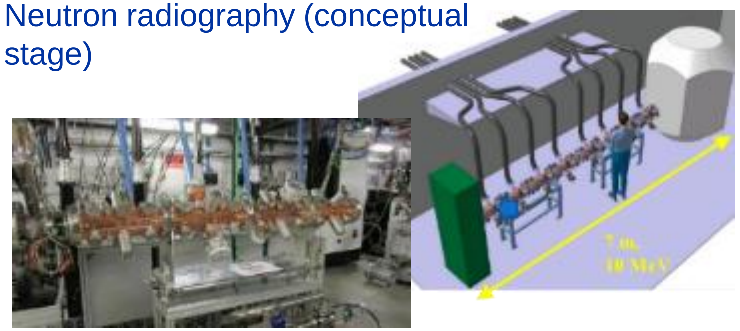
Important trend towards miniaturization of accelerators, for use in medicine and industry

Here are presented only three examples of recent developments at CERN:

## The mini-RFQ

750 MHz
92 mm diameter
2.5 MeV/m

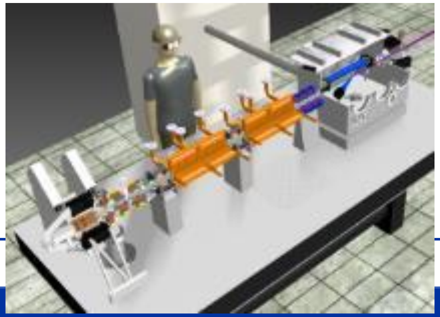
Proton therapy injector (in operation)
Artwork PIXE analysis (in construction, transportable)
Isotope production (design)
Neutron radiography (conceptual stage)



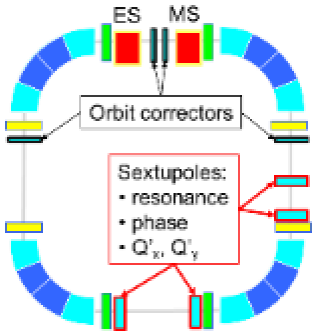
## X-band structures

12 GHz
100 MeV/m

Developed for CLIC, in operation at CLIC test stand
- Compact XFEL (CompactLight Design Study)
- VHEE and FLASH therapy linac (design)
- SmartLight (table top inverse Compton scattering light source, design)

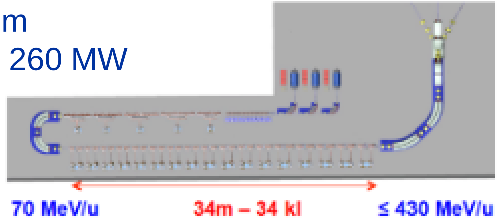


## Compact accelerators for ion therapy



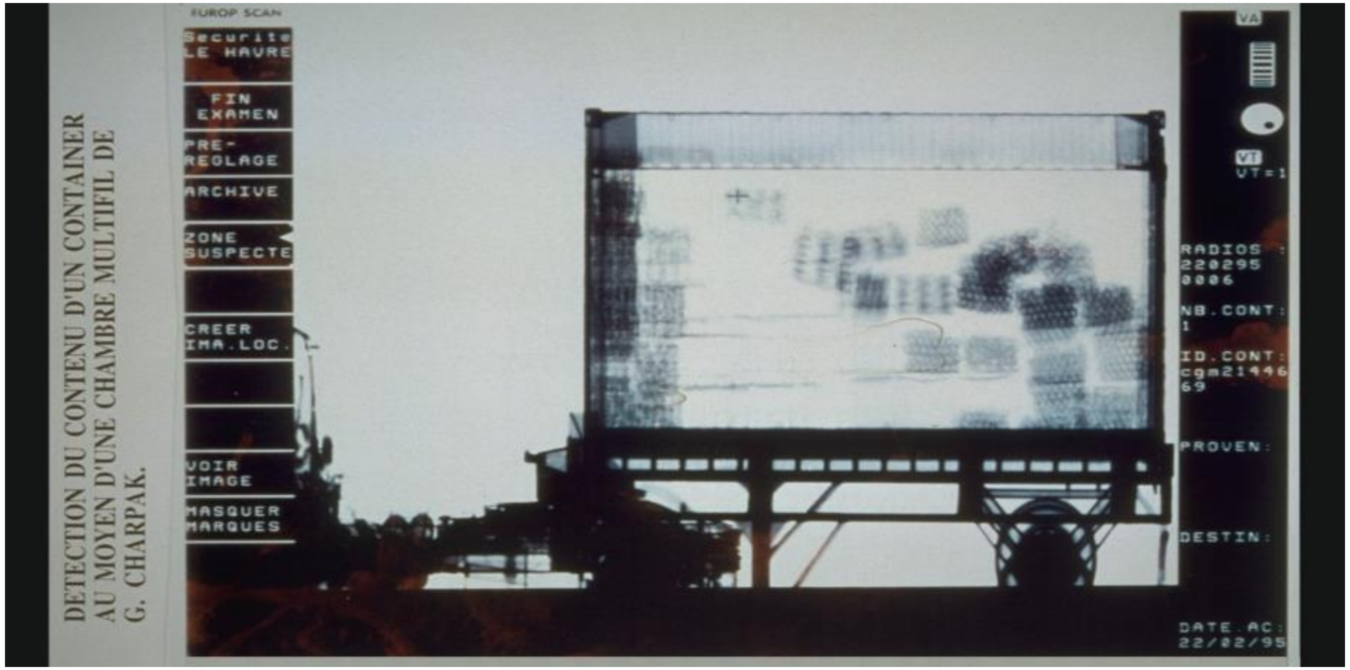
Superconducting C-ion synchrotron
Bmax 3.5 T
27m circumference

Folded C-ion linac,
Tot. length 53 m
Tot. RF power 260 MW



# Screening and security

# Cargo screening – X-ray



X-RAY IMAGING

Established screening technique in border control.

Source of electrons accelerated to several MeV, usually in a linac. Production of X-rays by bremsstrahlung (electrons decelerated by scattering inside a solid target).

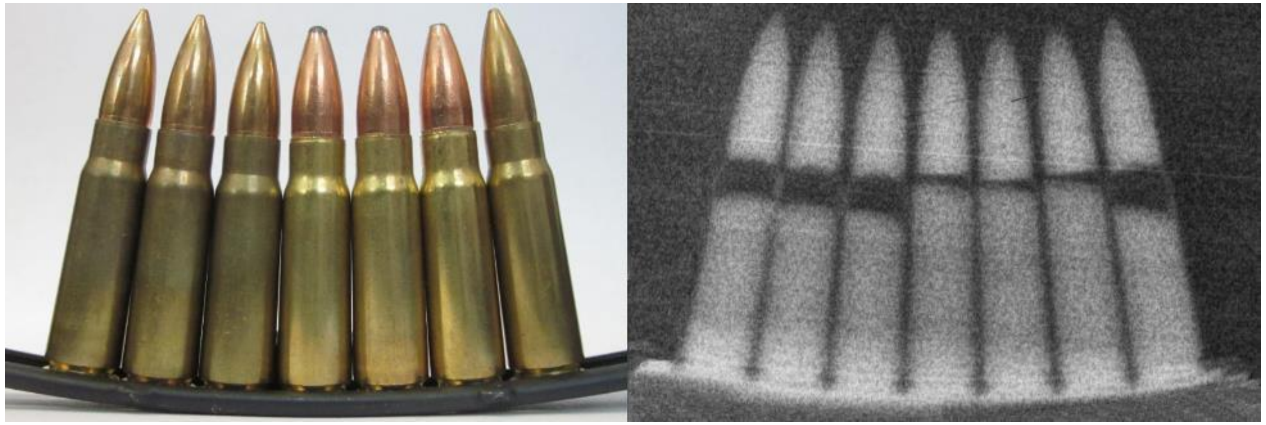
Significant dose rates according to the penetration and regulation requirements for a particular transport method and objects to be scanned.

# Cargo screening – neutrons

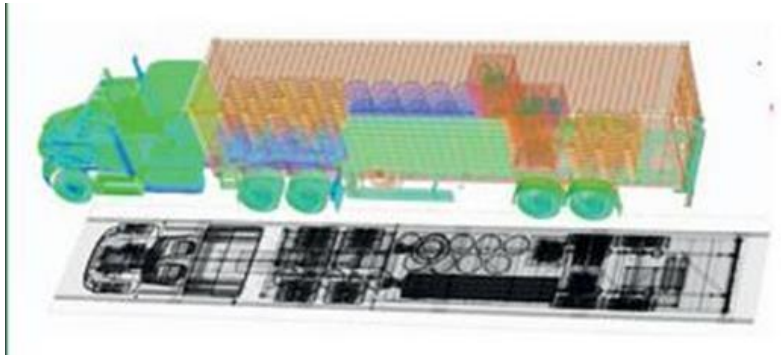
- Neutron radiography: detecting the neutrons transmitted through an object;
- Neutron-induced gamma spectroscopy: gamma-rays produced by neutron interactions with the cargo are detected.

Application to nuclear detection, e.g. of highly shielded nuclear materials. Neutron sources stimulate detectable fission in nuclear material.

Accelerators: acceleration of protons or deuterium to targets made of deuterium or tritium.



Pictures courtesy of Starfire Industries, USA



# Accelerators for energy

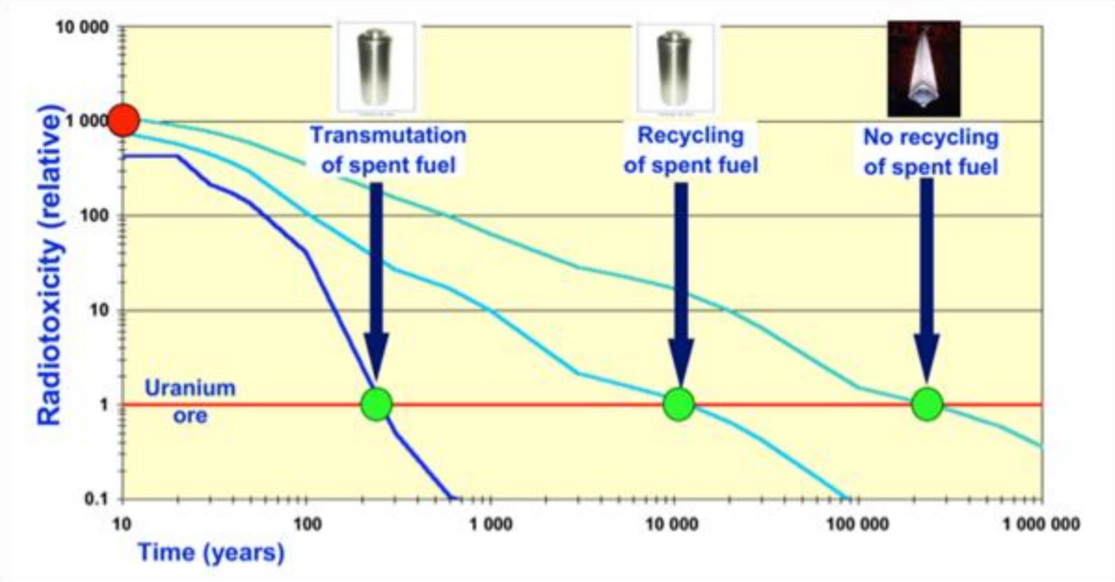
# Accelerators addressing the issues of nuclear power

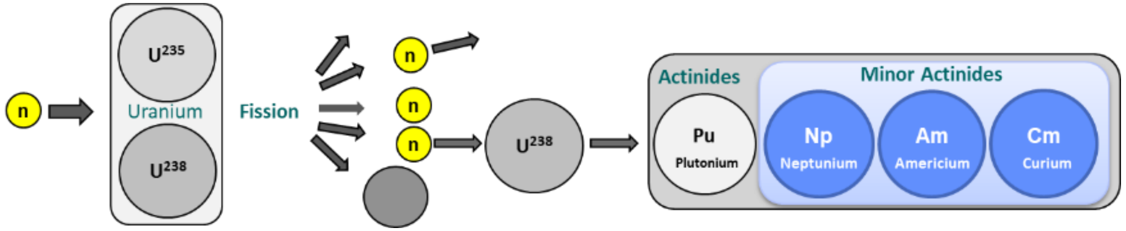
Main public concerns with nuclear power:

1. Risk of critical accidents
2. Long-term waste disposal
3. Risk of nuclear proliferation

The accelerator answer:

- Accelerator-driven sub-critical operation
- Waste treatment (transmutation) with accelerators
- Thorium-based reactors





Transmutation of Minor Actinides (heavier radioactive isotopes of neptunium, americium and curium) requires a fast-neutron system, possibly not reactor-based.

# Accelerator-driven transmutation

**MYRRHA Project**

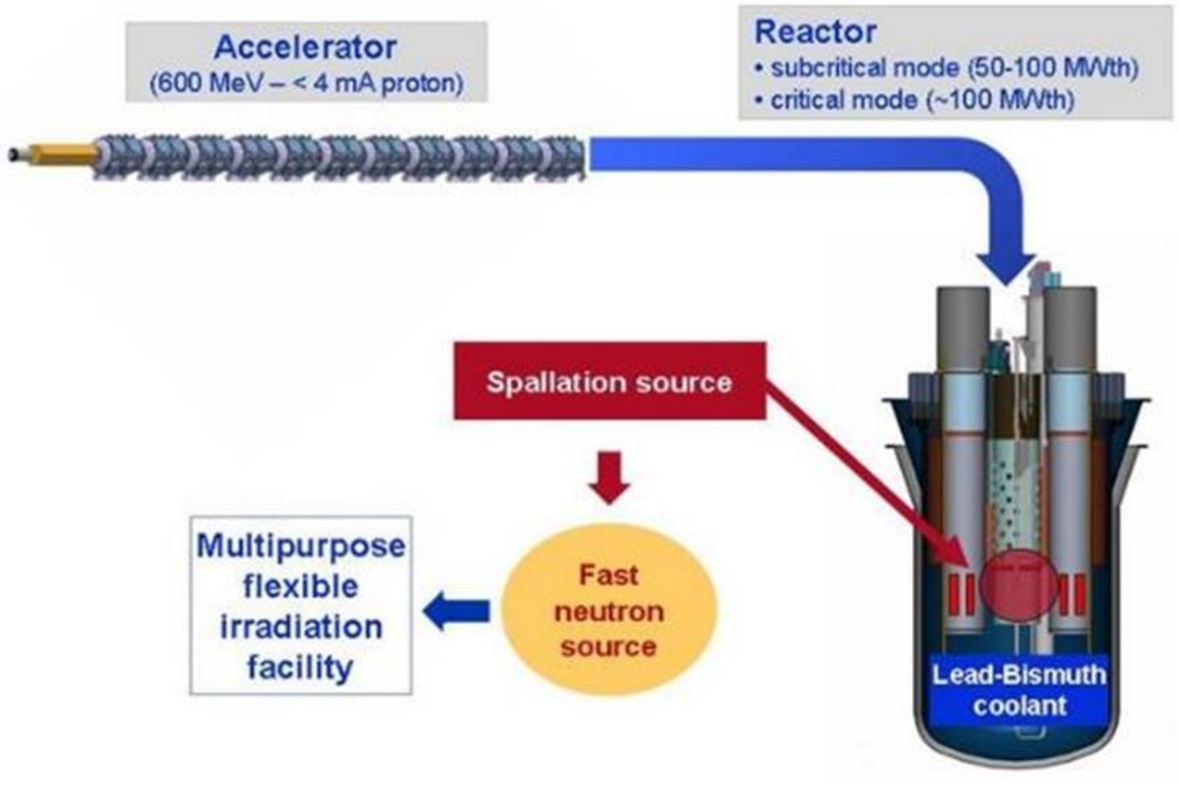
**Multi-purpose hYbrid Research Reactor for High-tech Applications)**

*Development, construction & commissioning of a new large fast neutron research*

**❶ ADS demonstrator**

**❷ Fast neutron irradiation facility**

**❸ Pilot plant for LFR technology**



Three elements:

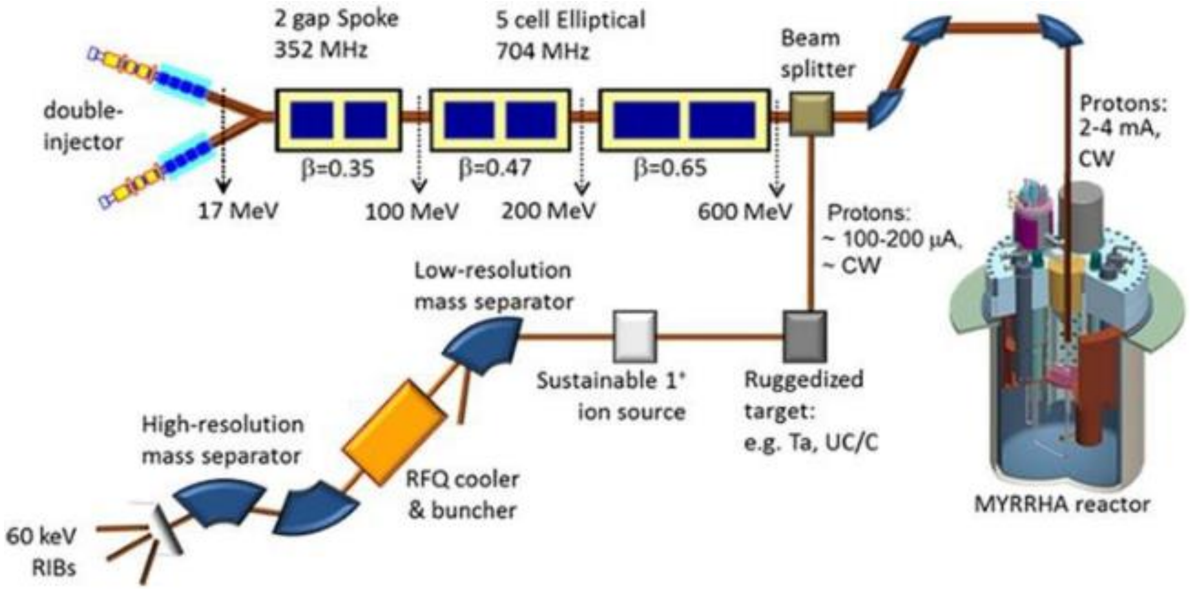
- subcritical reactor core,
- spallation target
- particle accelerator

Advantage: large quantities (<40% of core) of MAs loaded for transmutation.

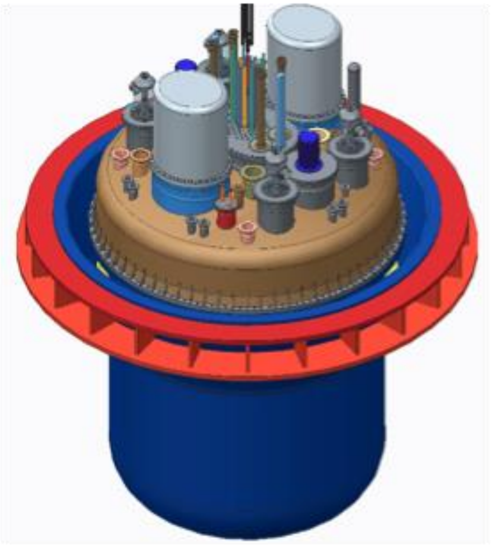
Small number of dedicated ADS transmutation systems in Europe burn the waste from a large number of fast reactors for electricity generation.

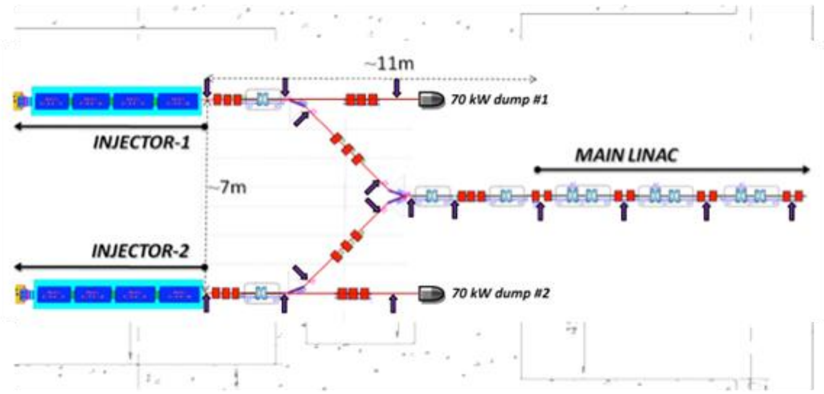
# The MYRRHA project

SCK-CEN project at Mol, Belgium

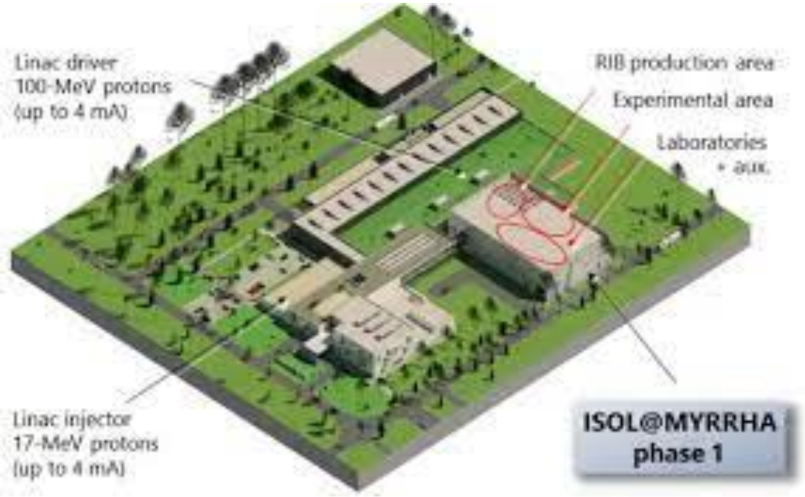


*Layout of the MYRRHA reactor vessel*





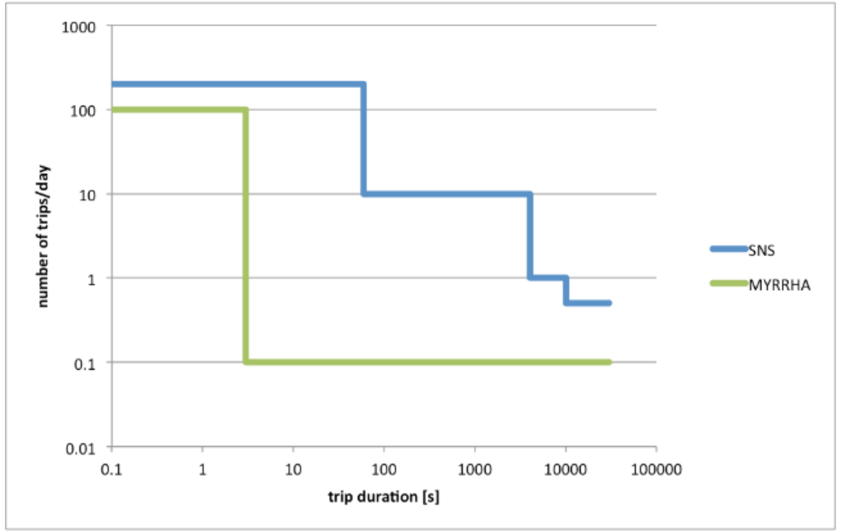
*General layout of the 17 MeV MYRRHA Medium Energy Beam Transport section, that links the two injectors with the higher energy "fault-tolerant" main superconducting linac*



# The reliability challenge

- Beam trips longer than 1 sec are forbidden to avoid thermal stresses & fatigue on the ADS target, fuel & assembly & to provide good plant availability.
- Present SPECIFICATIONS

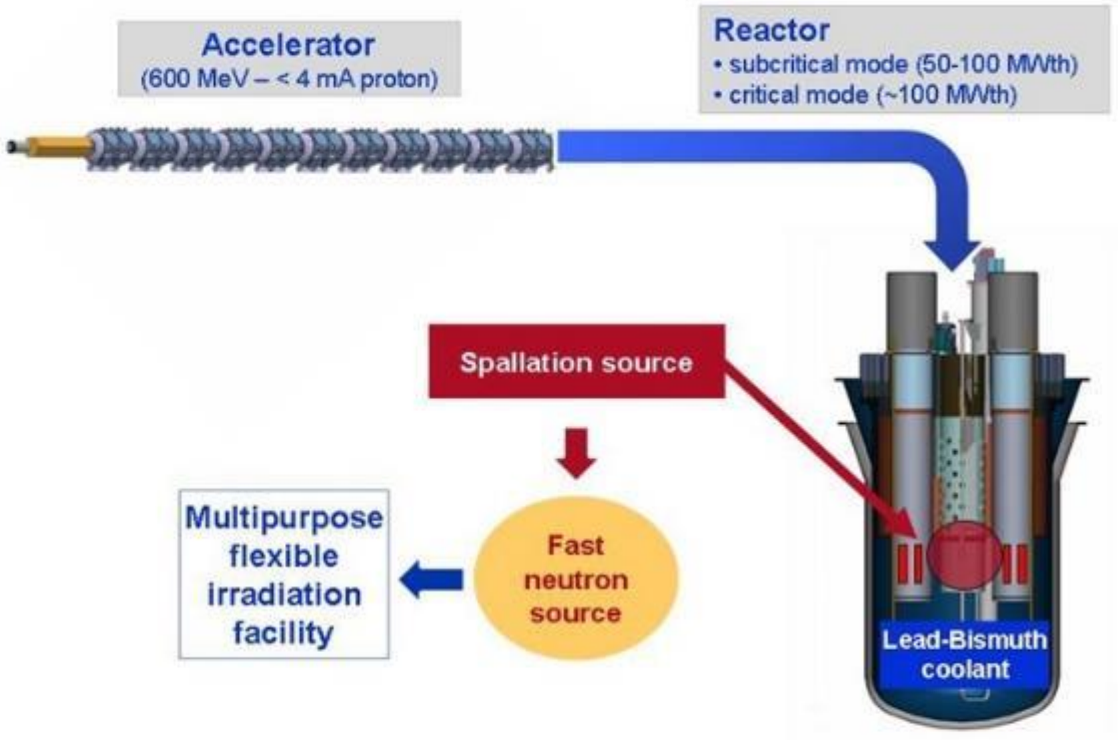
  Less than 5-10 beam trips (>1-3sec) per 3-month operation cycle



Reliability guidelines have been followed during the ADS accelerator design

1. Strong component design (“overdesign”)
   - All components are derated with respect to technological limitations
2. Inclusion of redundancies in critical areas
   - Doubled front-end (hot stand-by injector), solid-state RF power amplifiers where possible…
3. Enhance the capability of fault-tolerant operation
   - “Fault-tolerance” = ability to pursue operation despite some major faults in the system
   - Expected in the independently-phased superconducting linac, especially for RF faults (RF systems = critical reliability area)

# Accelerator Driven Systems



A linac coupled to a spallation source provides the missing neutrons to maintain the reaction in a subcritical reactor.

Could be used for energy production allowing alternative fuel cycles (thorium) and with no safety concerns (subcritical).

| Pros | Cons |
|---|---|
| Safety: subcritical reaction, allows for immediate switch-off | High reliability (→cost) required for the accelerator, to protect structures from thermal shocks |
| Possibility to operate below criticality opens the way to new reactor concepts | Reduction in net plant power efficiency due to power consumption of accelerator |
| Simple reactor control by modulating accelerator current | Increased complexity (and cost) |

# Roadmap of ADS project in China

2014.06, 2.1 MeV/10 mA/CW

Goal in 2015.06, 5 MeV

Injector II, 162.5 MHz

Goal in 2015.12, 10 MeV

Goal in 2016.09, 25 MeV

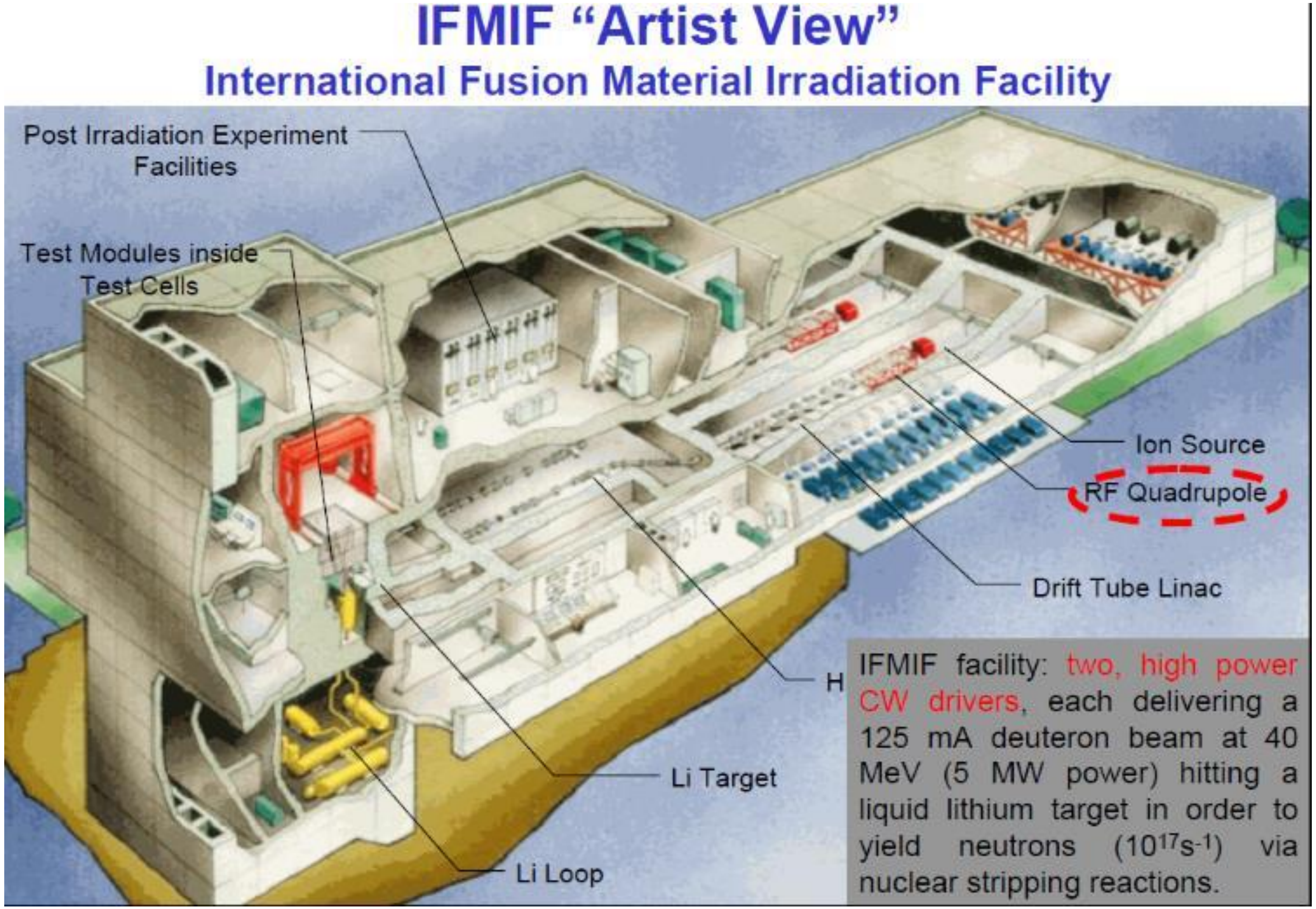
Injector I, 325 MHz

Stage 1: Research facility (CIADS)
(250 MeV, 10 mA, 10 MWt)
Y2017-2022, 2.25 B CNY

“Strategic Technology Pilot Project”
of the Chinese Academy of Sciences
Key technology R&D
Y2011-2017, 1.78 B CNY

Stage 2: Demo facility (CDADS)
(1.2~1.5GeV, 10~25 mA, 100 MWt)
Y2030

# Accelerators for fusion material testing: IFMIF


IFMIF “Artist View”

International Fusion Material Irradiation Facility

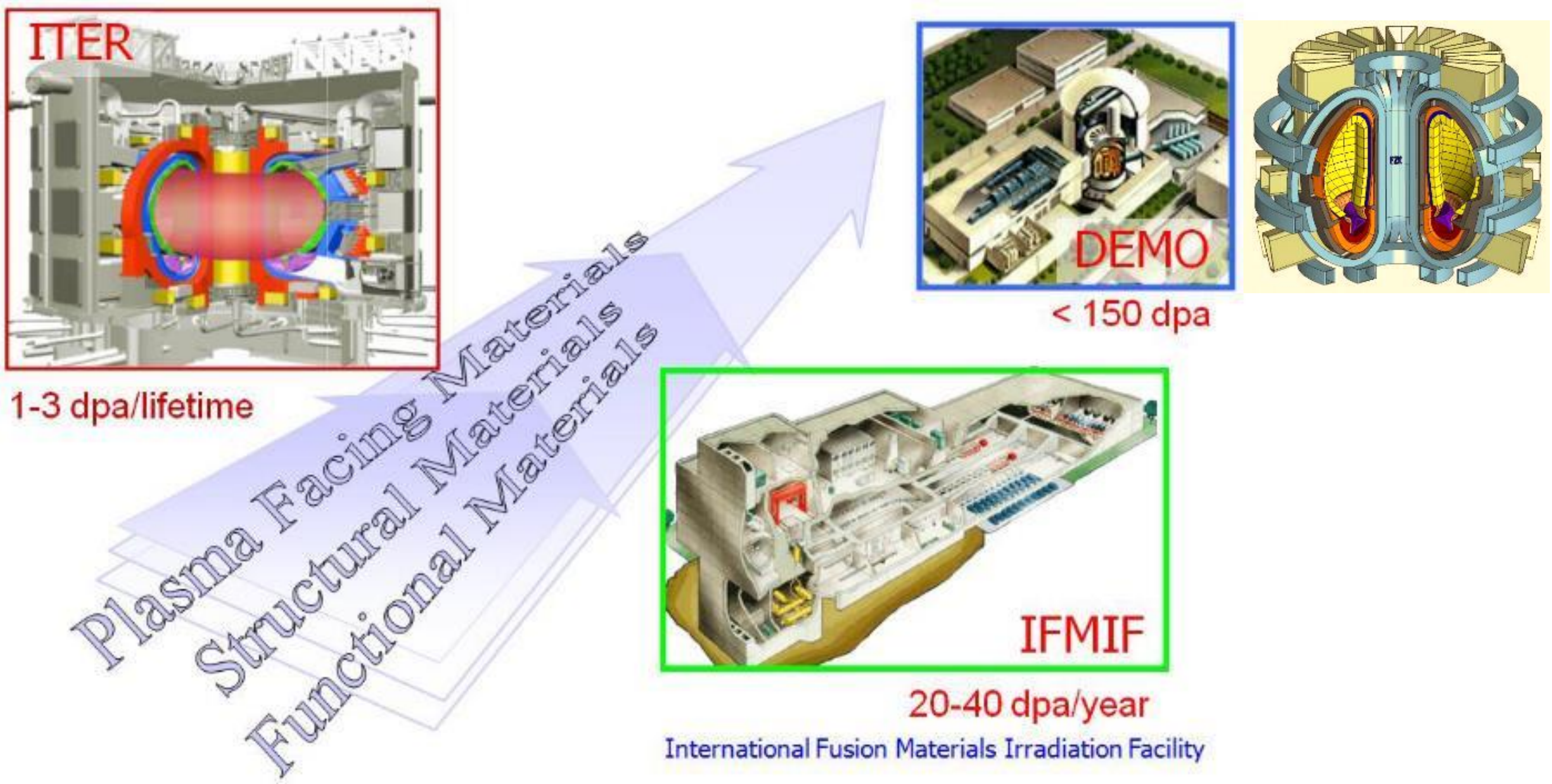
IFMIF facility: two, high power CW drivers, each delivering a 125 mA deuteron beam at 40 MeV (5 MW power) hitting a liquid lithium target in order to yield neutrons $(10^{17}s^{-1})$ via nuclear stripping reactions.

*Test under strong neutron fluxes of materials to be used in ITER*

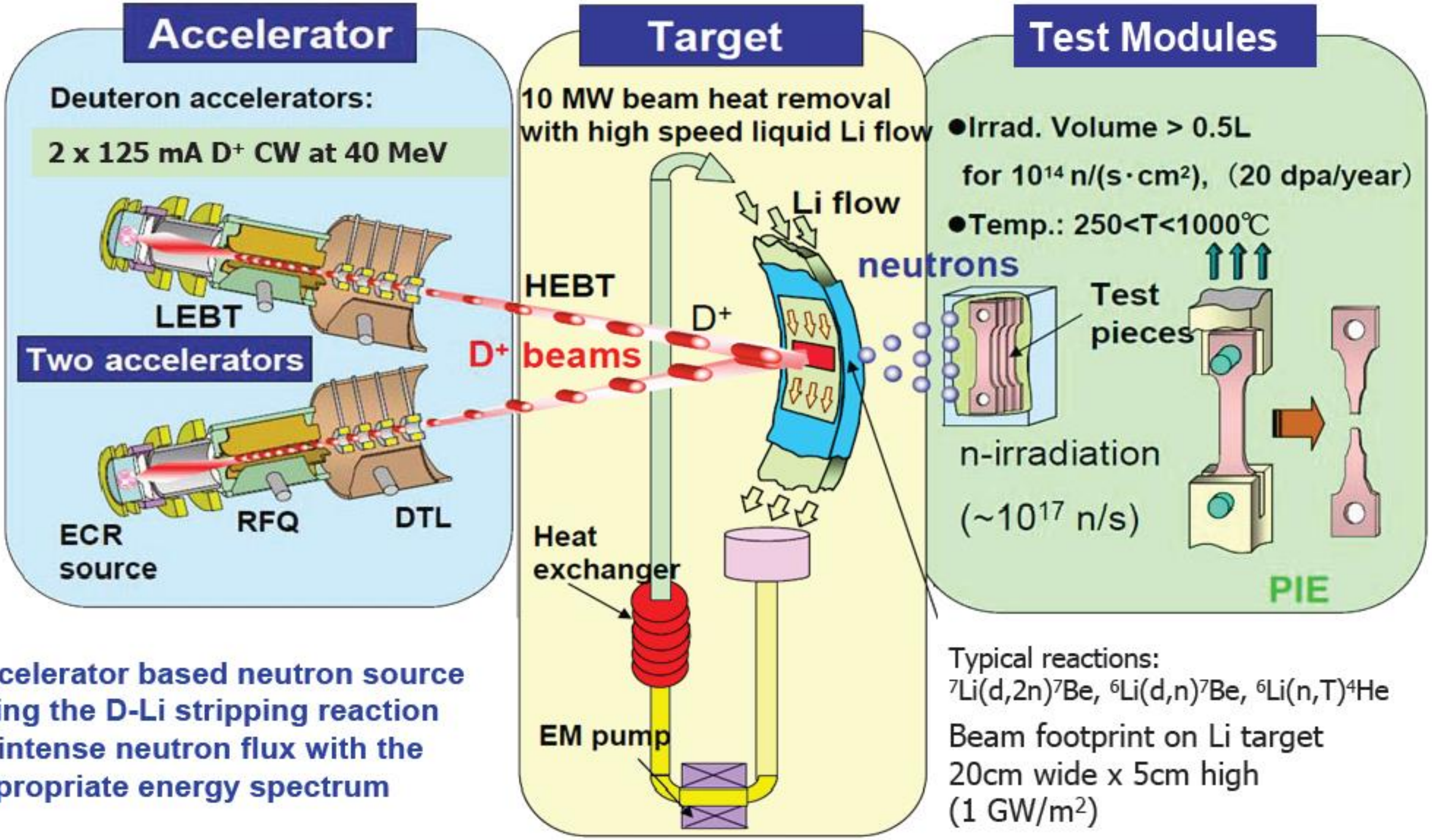
# Advanced materials on the critical path to fusion

**DEMO = Fusion Power Plant Demonstrator (after ITER)**

Fusion Power: 2.5 GW ( x 5 ITER )
Reactor Efficiency: 37-45%



# IFMIF principles



**Accelerator**

Deuteron accelerators:

2 x 125 mA $D^+$ CW at 40 MeV

**Target**

10 MW beam heat removal with high speed liquid Li flow

**Test Modules**

- Irrad. Volume > 0.5L for $10^{14}$ n/(s·cm$^2$), (20 dpa/year)
- Temp.: 250<T<1000℃

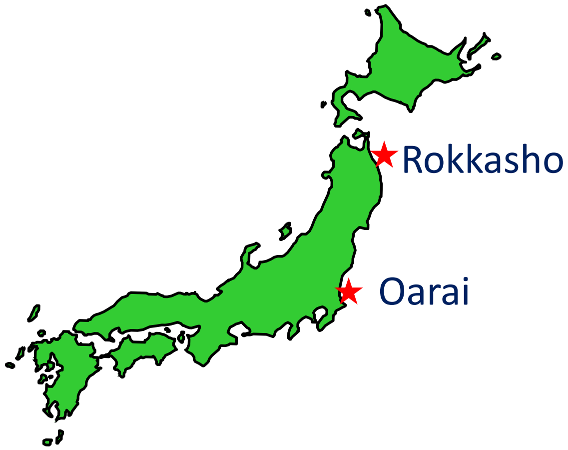
Accelerator based neutron source using the D-Li stripping reaction ⇒ intense neutron flux with the appropriate energy spectrum

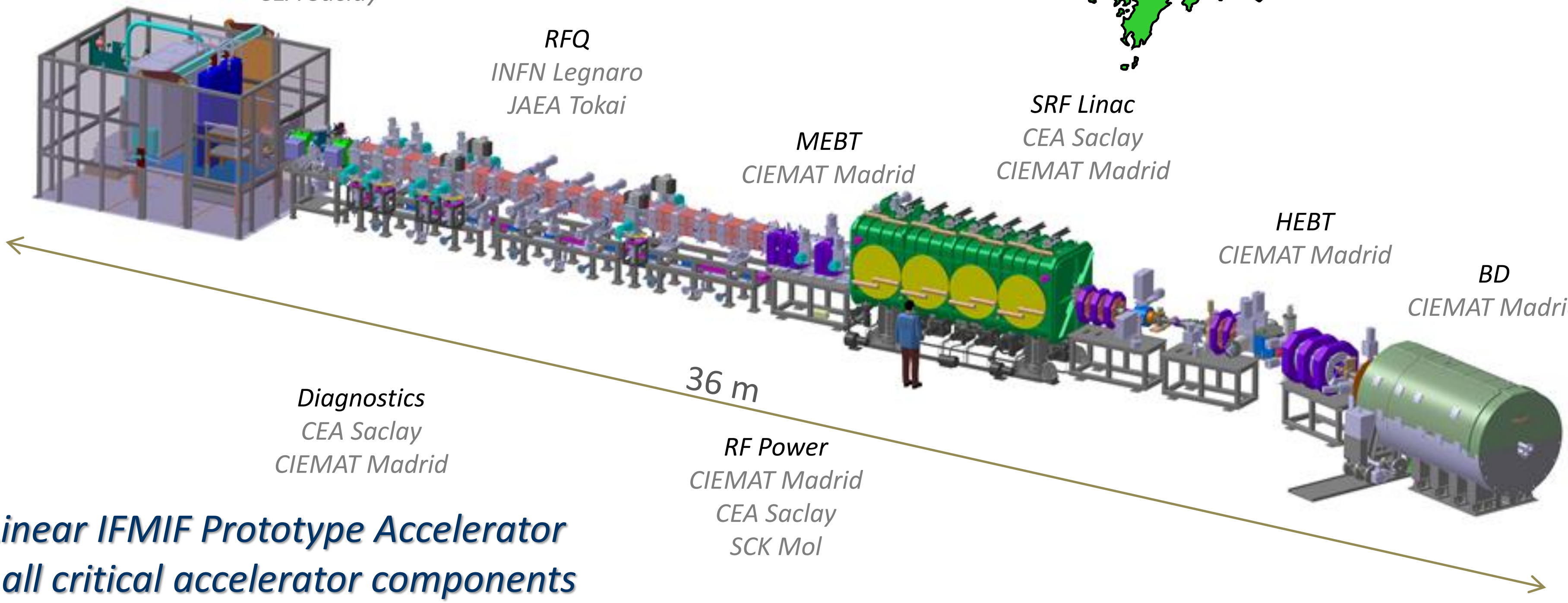
Typical reactions:
$^7Li(d,2n)^7Be$, $^6Li(d,n)^7Be$, $^6Li(n,T)^4He$

Beam footprint on Li target
20cm wide x 5cm high
(1 GW/m$^2$)

# LIPAc test accelerator

Installed and commissioned in Rokkasho (Japan) with European accelerator components





*Injector + LEBT*
*CEA Saclay*

*RFQ*
*INFN Legnaro*
*JAEA Tokai*

*MEBT*
*CIEMAT Madrid*

*SRF Linac*
*CEA Saclay*
*CIEMAT Madrid*

*HEBT*
*CIEMAT Madrid*

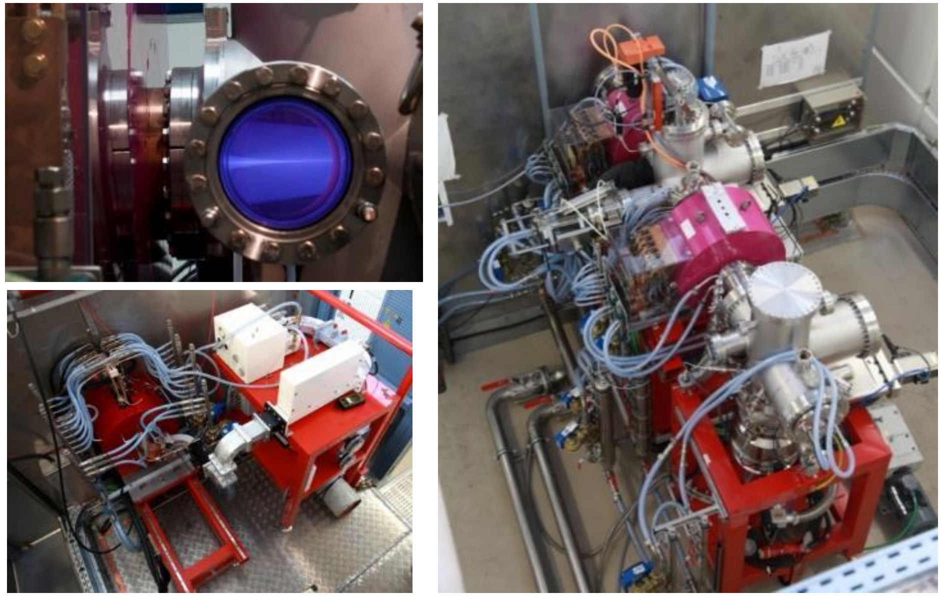
*BD*
*CIEMAT Madrid*

*Diagnostics*
*CEA Saclay*
*CIEMAT Madrid*

*RF Power*
*CIEMAT Madrid*
*CEA Saclay*
*SCK Mol*

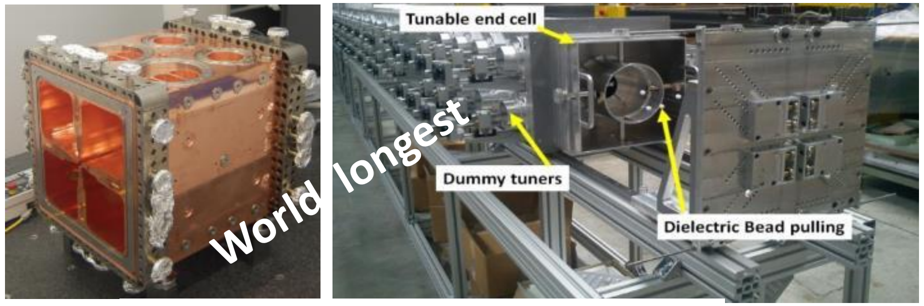
***LIPAc = Linear IFMIF Prototype Accelerator***
***includes all critical accelerator components***
***to be tested at nominal beam current at BA site***

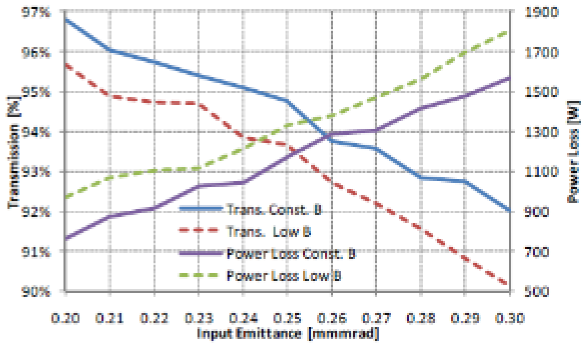
## Injector (CEA, Saclay)



$D^+$ (95% species fraction)
Ion Source ECR (2.45 GHz) - CW
E = 100 keV
I = 140 mA
emittance of 0.25 π mm·mrad
Availability > 95%

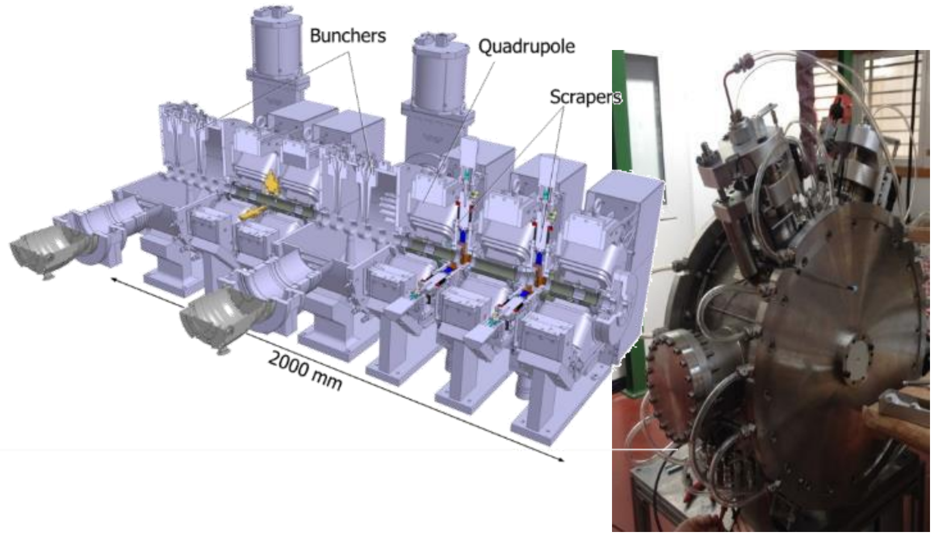
## RFQ (INFN, Legnaro)





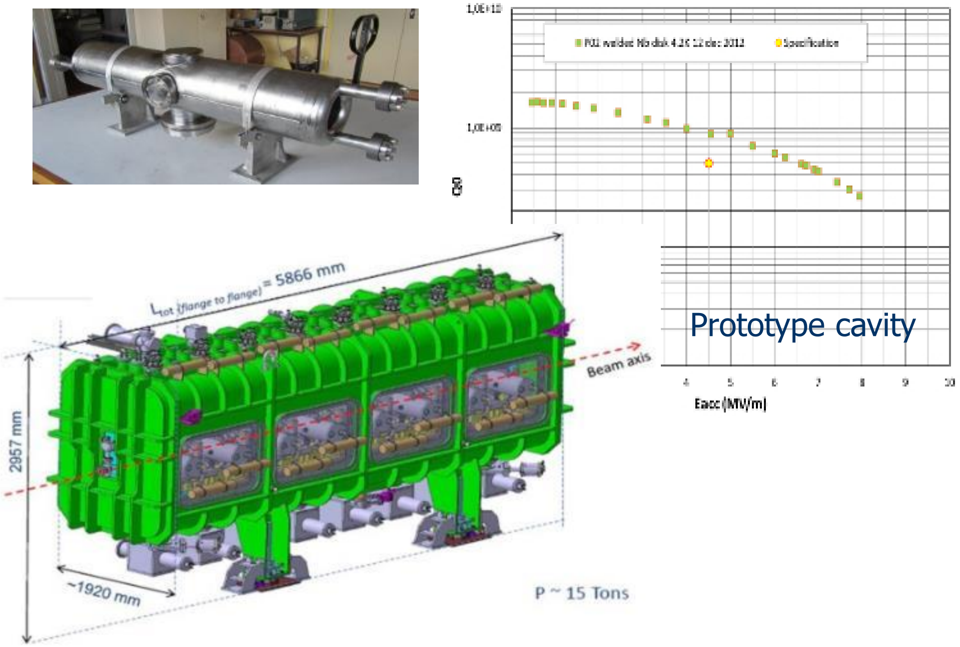
175 MHz; $I_{input}$= 130 mA ; $E_{out}$= 5 MeV
Up to 10mA beam losses allowed
Max surface field 25.2 MV/m (1.8 Kp)
18 module (9.8 m long)
Tuning demonstrated in an Al full scale prototype

## MEBT (CIEMAT, Madrid)



very compact ~ 2 m, many components
5 quadrupoles & steering coils
2 bunchers (5 gaps IH), 2 movable scrapers
BPMs (in the center of quads)
turbomolecular pumps on bunchers
(1300 l/s /buncher)

## SRF Cryomodule (CEA, Saclay)

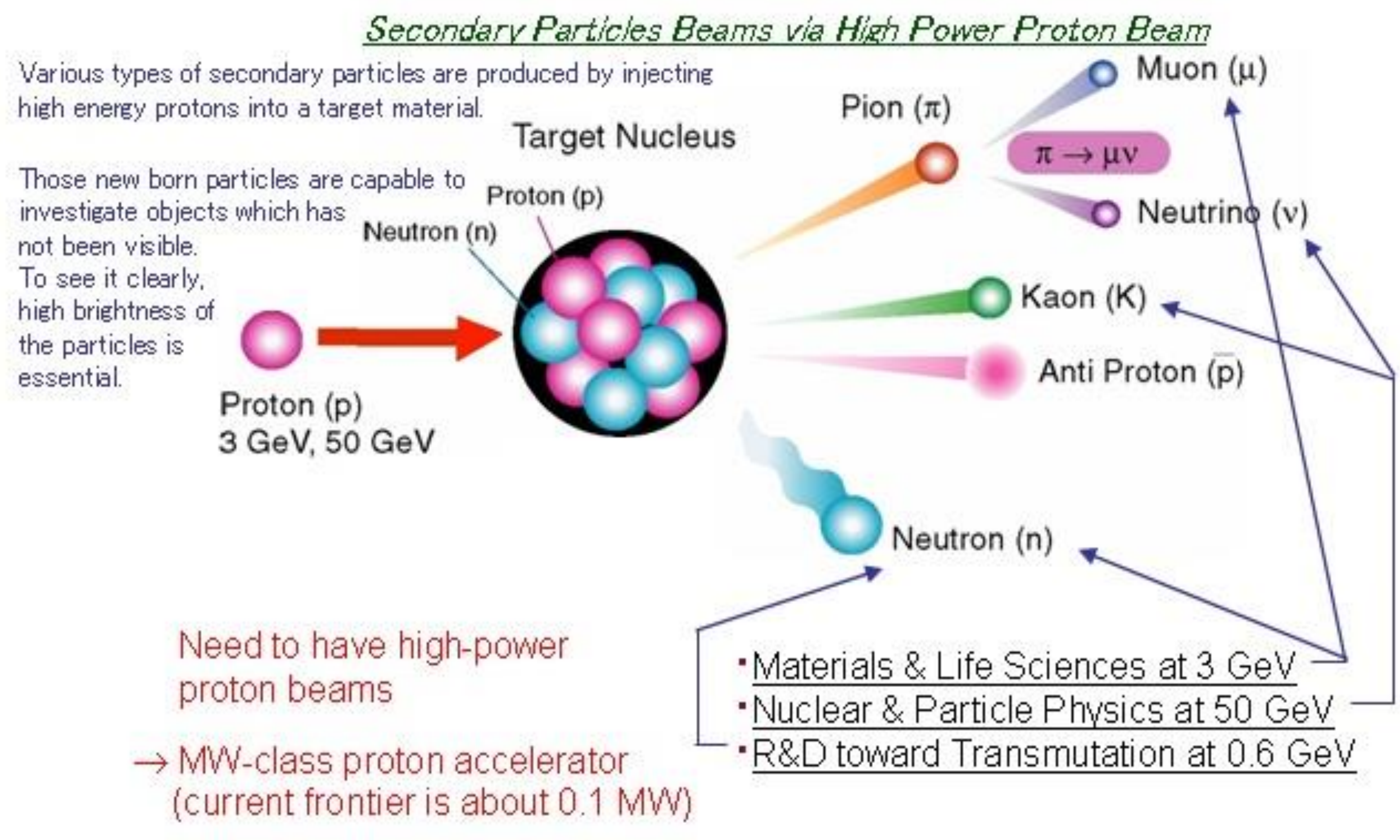


Prototype cavity

8 resonators ($\beta$=0.094) $E_{acc}$=4.5 MeV/m
8 solenoid packages + steerers & BPM
Max transm. RF power = 70 kW
Cavity licensing process unexpectedly difficult and time consuming

# Accelerators for neutron production

# Secondary particle beams



Secondary Particles Beams via High Power Proton Beam

Various types of secondary particles are produced by injecting high energy protons into a target material.

Those new born particles are capable to investigate objects which has not been visible.
To see it clearly, high brightness of the particles is essential.

Need to have high-power proton beams

→ MW-class proton accelerator (current frontier is about 0.1 MW)

- Materials & Life Sciences at 3 GeV
- Nuclear & Particle Physics at 50 GeV
- R&D toward Transmutation at 0.6 GeV

*(courtesy of JPARC)*

. Energy production (Accelerator Driven Systems), > 2 GeV
. Radiactive Ion Beams (ISOL), > 1 GeV

# Beam power

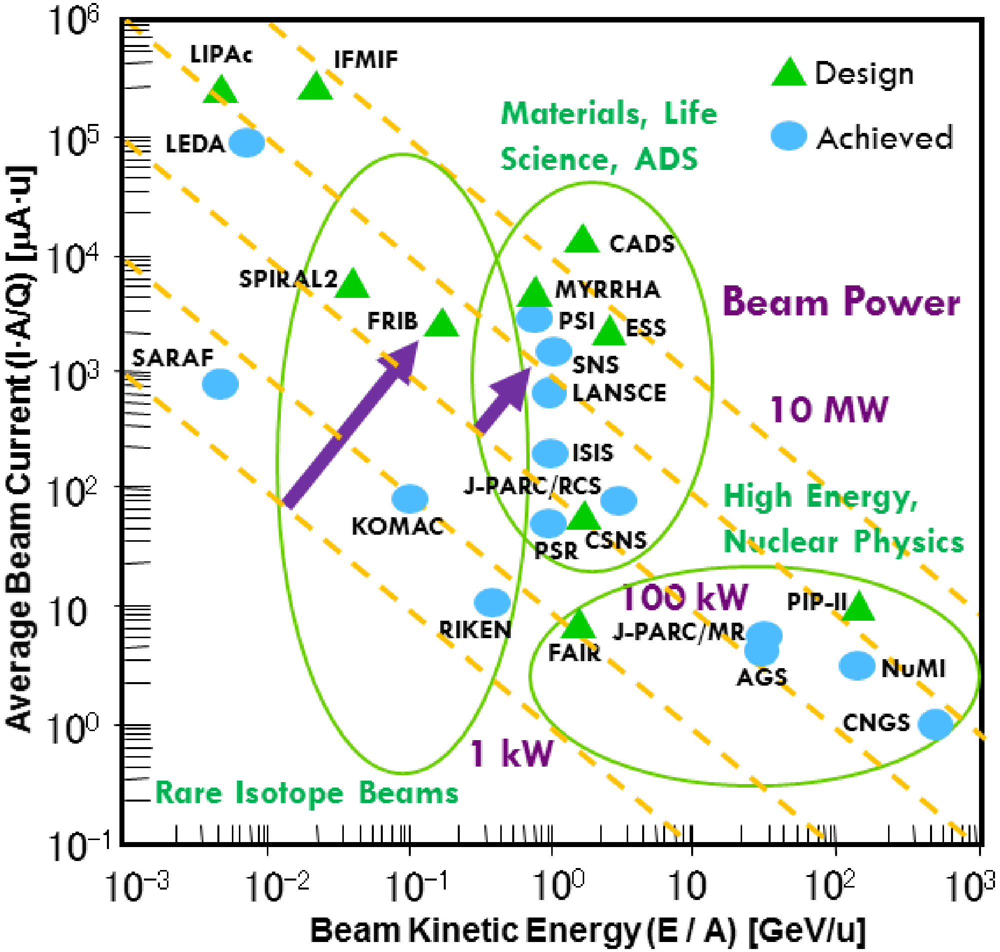


Figure of merit for accelerators at the intensity frontier is beam power P=W×I×duty cycle

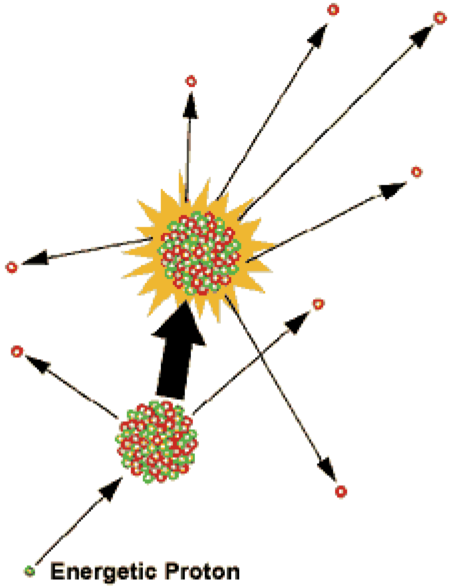
Production rate (cross-section) for most of the particles in high-intensity applications is independent on the energy (above a certain threshold) but proportional to beam power.

The new generation of accelerators under project or construction aims at moving the power from the 100 kW's range to the MW's range.

A MW-class machine presents a large number of challenges and requires the development of specific technologies.

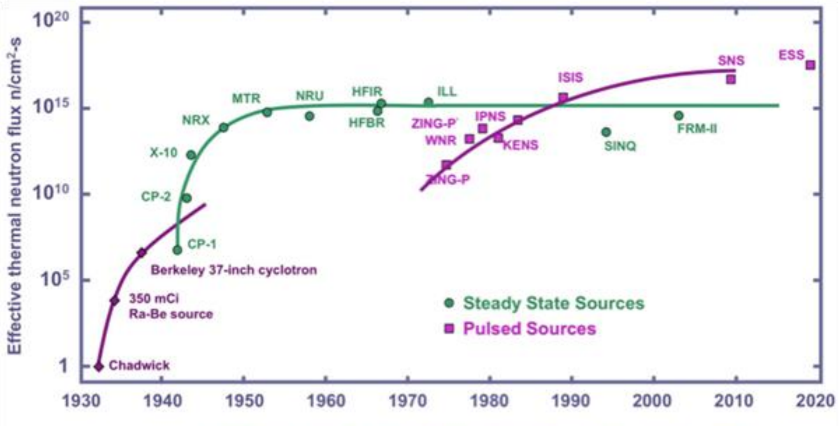
# Neutron scattering: Spallation Neutron Sources

Neutrons are ideal probes to map the molecular and magnetic structure and behavior of materials (high-temperature superconductors, polymers, metals), and biological samples → Application to fundamental physics, structural biology and biotechnology, magnetism and superconductivity, chemical and engineering materials, nanotechnology, complex fluids, ...



Traditionally, neutrons were produced by nuclear reactors; nowadays, are used linear accelerators at energy ≥ 1 GeV

2 linac-based facilities operational (SNS at Oak Ridge – USA and J-PARC at Tokai – Japan) and a third is in construction (European Spallation Source at Lund – Sweden).

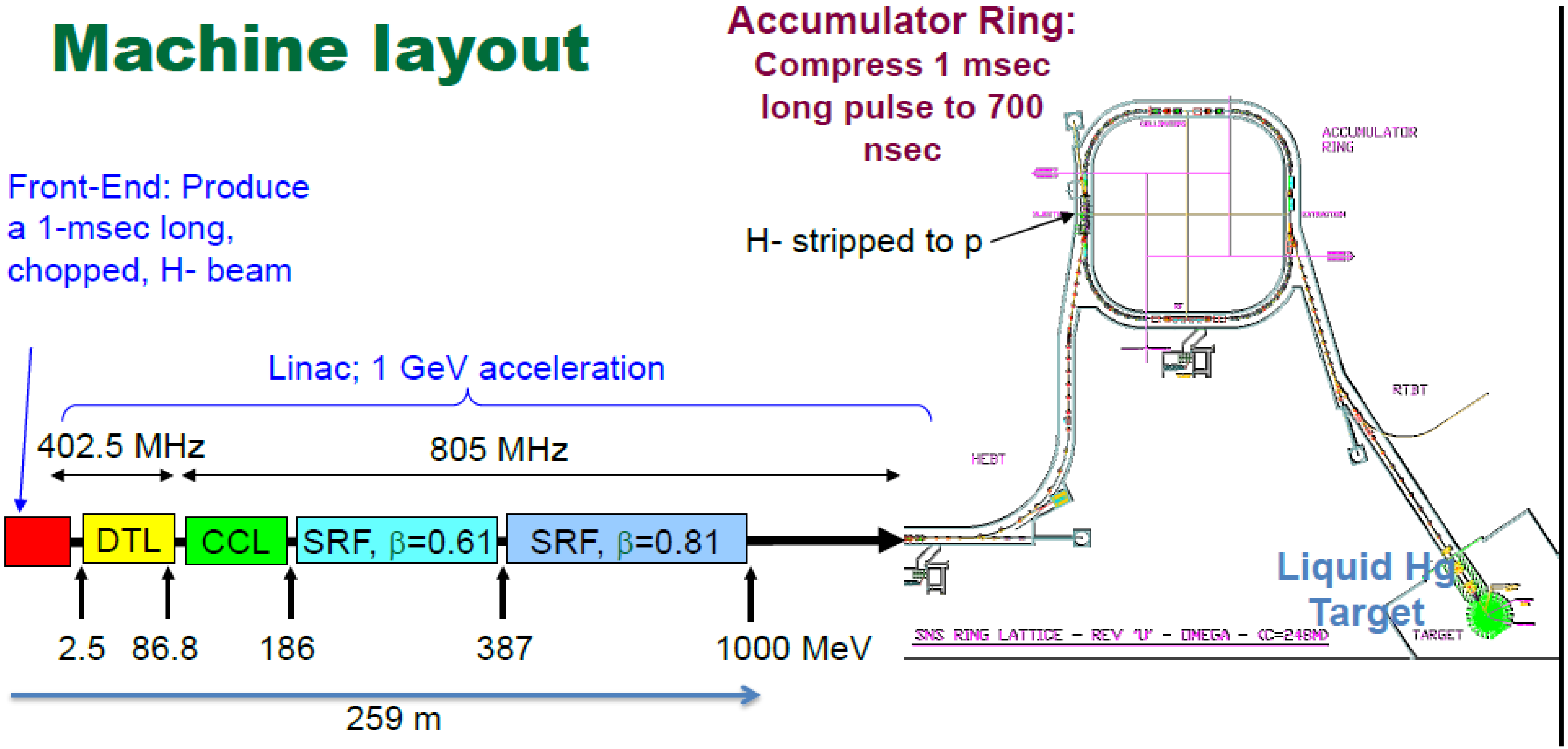


(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

# US Spallation Neutron Source

US Spallation Neutron Source (Oak Ridge)
World's highest power proton source (1 MW)
1 GeV, 5% duty

# SNS - layout



## Machine layout

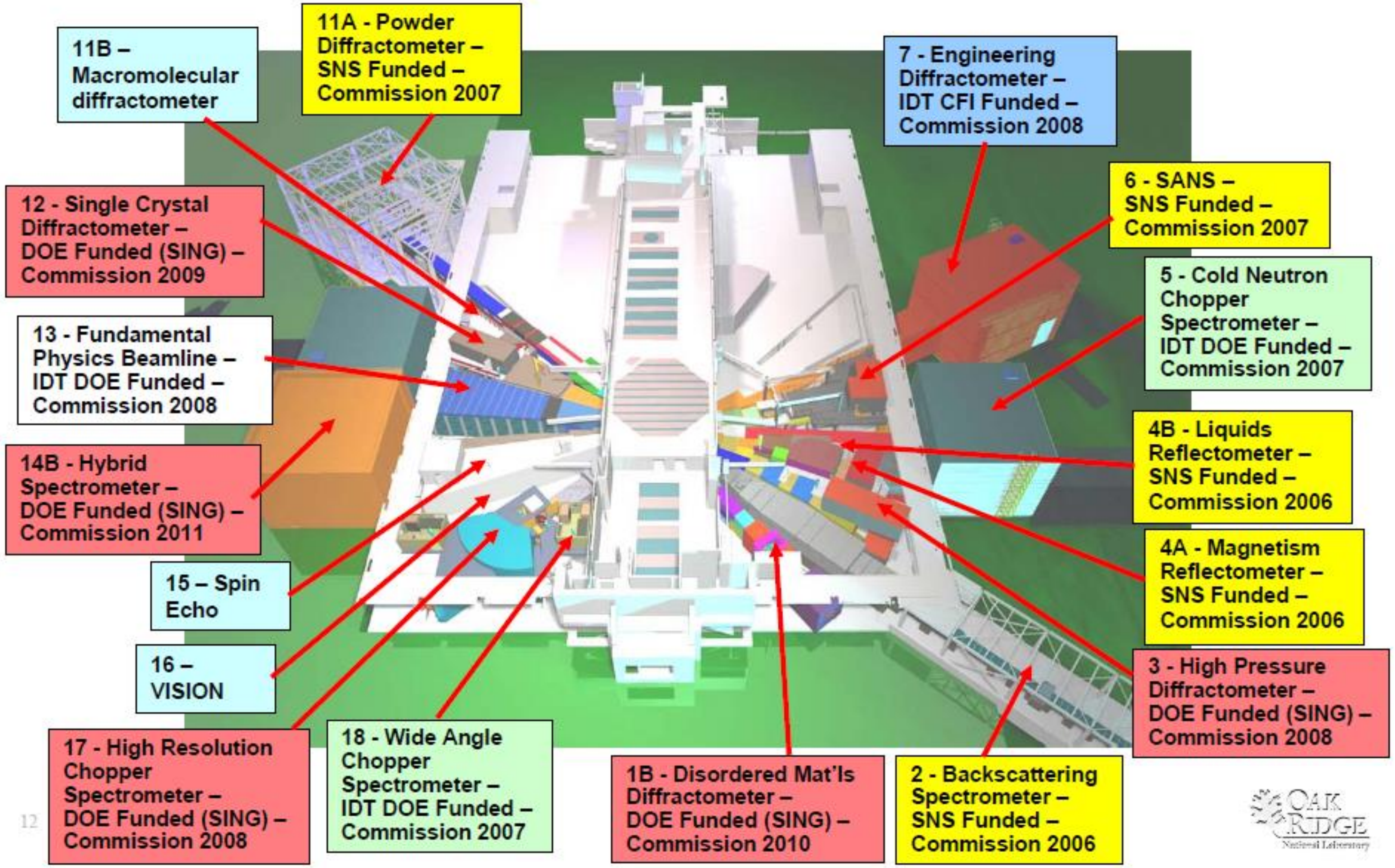
**Accumulator Ring: Compress 1 msec long pulse to 700 nsec**

Front-End: Produce a 1-msec long, chopped, H- beam

H- stripped to p

Linac; 1 GeV acceleration

# SNS – Scientific Program



11B – Macromolecular diffractometer

11A - Powder Diffractometer – SNS Funded – Commission 2007

12 - Single Crystal Diffractometer – DOE Funded (SING) – Commission 2009

13 - Fundamental Physics Beamline – IDT DOE Funded – Commission 2008

14B - Hybrid Spectrometer – DOE Funded (SING) – Commission 2011

15 – Spin Echo

16 – VISION

17 - High Resolution Chopper Spectrometer – DOE Funded (SING) – Commission 2008

18 - Wide Angle Chopper Spectrometer – IDT DOE Funded – Commission 2007

1B - Disordered Mat'ls Diffractometer – DOE Funded (SING) – Commission 2010

2 - Backscattering Spectrometer – SNS Funded – Commission 2006

3 - High Pressure Diffractometer – DOE Funded (SING) – Commission 2008

4A - Magnetism Reflectometer – SNS Funded – Commission 2006

4B - Liquids Reflectometer – SNS Funded – Commission 2006

5 - Cold Neutron Chopper Spectrometer – IDT DOE Funded – Commission 2007

6 - SANS – SNS Funded – Commission 2007

7 - Engineering Diffractometer – IDT CFI Funded – Commission 2008

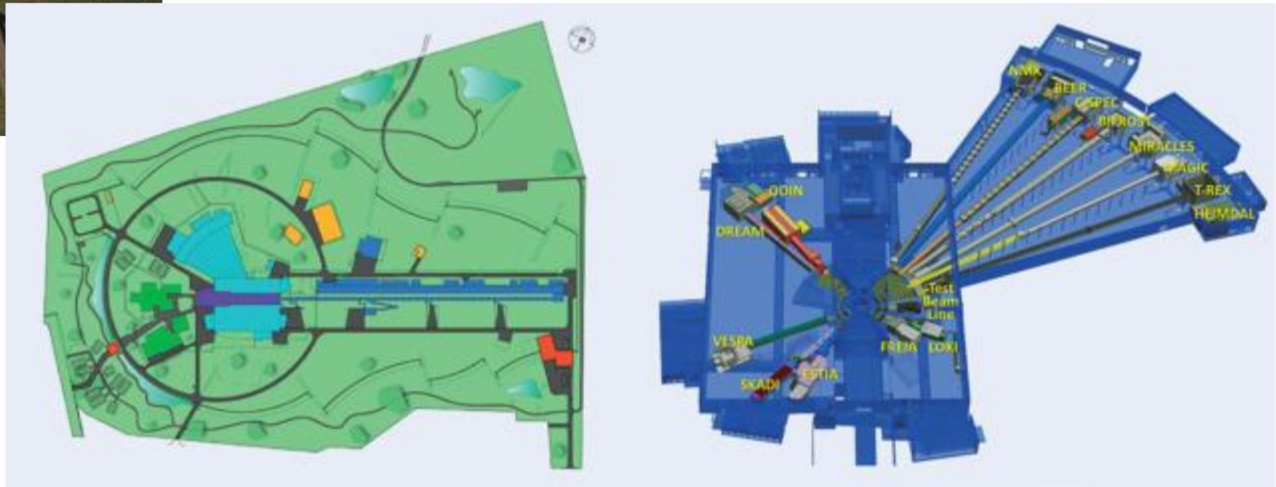
# European Spallation Source

The ESS is being built in Lund (Sweden).

Will provide the EU neutron science community with a modern facility

5 MW long-pulse: no need of an accumulator/compressor like SNS.

He-cooled rotating tungsten wheel target (to avoid management of activated Hg as in SNS).



# ESS accelerator technical performance

Design Drivers:

High Average Beam Power

5 MW

High Peak Beam Power

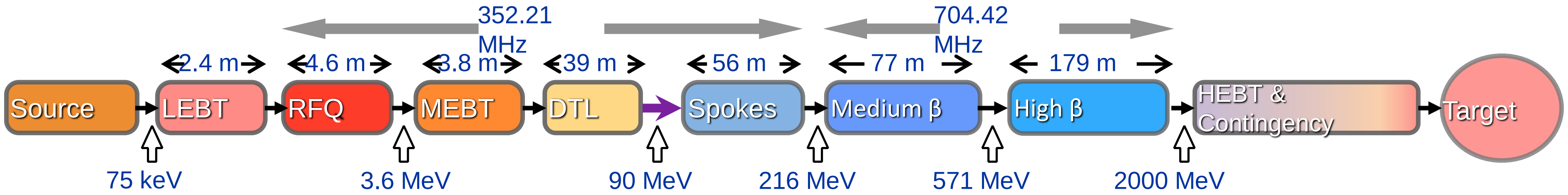
125 MW

High Availability

> 95%

Key parameters:

-2.86 ms pulses
-2 GeV
-62.5 mA peak
-14 Hz
-Protons (H+)
-Low losses
-Minimize energy use
-Flexible design for mitigation and future upgrades



352.21 MHz

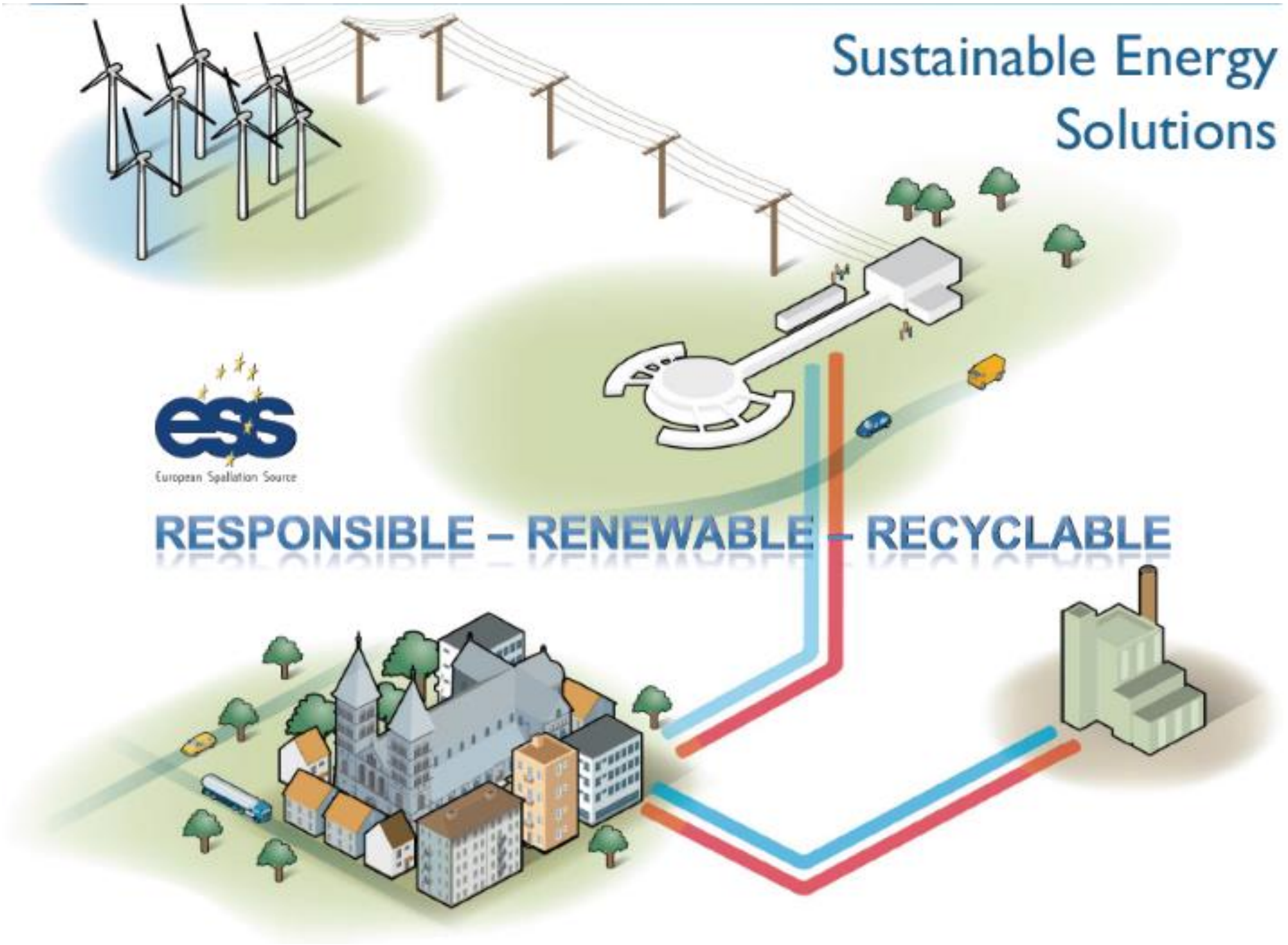
704.42 MHz

2.4 m, 4.6 m, 3.8 m, 39 m, 56 m, 77 m, 179 m

Source → LEBT → RFQ → MEBT → DTL → Spokes → Medium β → High β → HEBT & Contingency → Target

75 keV, 3.6 MeV, 90 MeV, 216 MeV, 571 MeV, 2000 MeV

# ESS Energy Management



Modern facilities like the ESS need to be “green”, to be accepted socially and politically and to prepare for a sustainable future.

⇩

This is an important technical challenge involving:

-Higher efficiency RF;

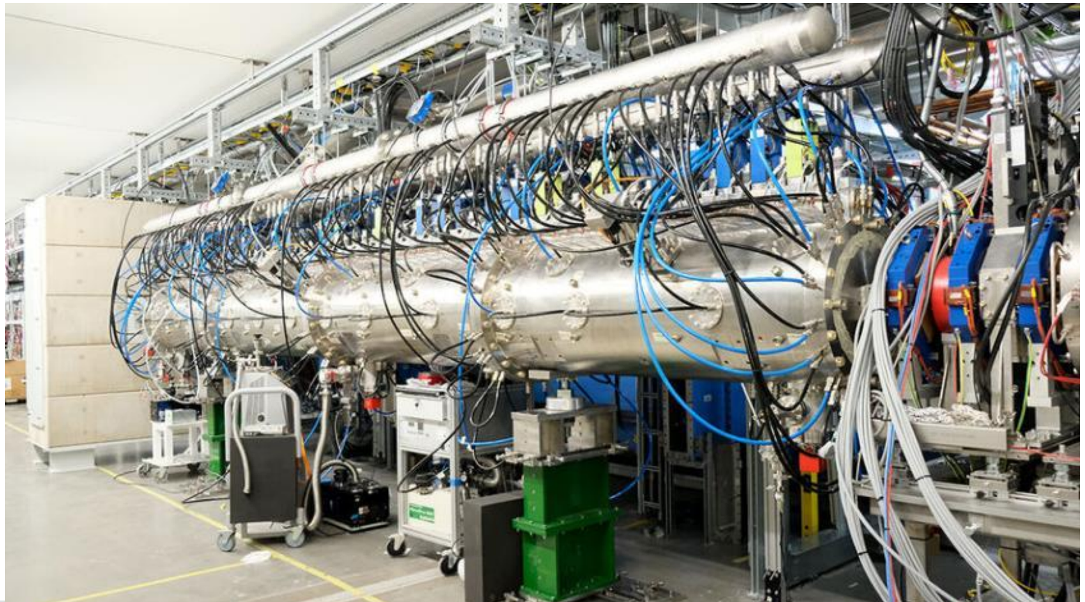
-Recuperation of cooling water (operation at higher temperature and pressure);

-More PMQ-based beam transport

# ESS commissioning progress - 2022

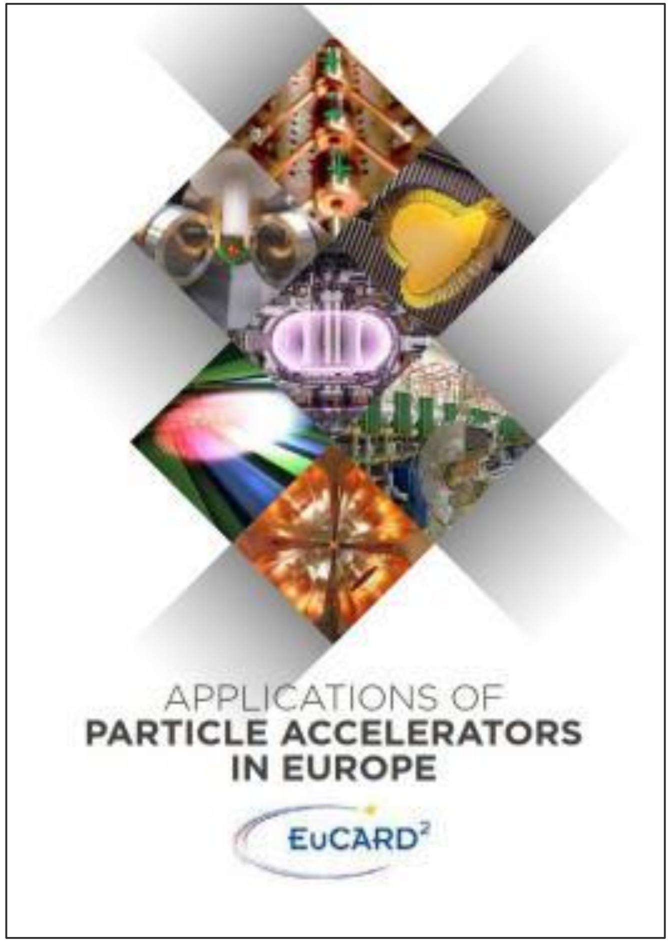
*Cryomodule Prototype inside the Test Stand*

*Ion Source inaugurated*
*by the Italian president*



*1st DTL tank installed*

# Acknowledgement and further reading



Many of the pictures and some text of this lecture have been taken from the 2017 EuCARD2 Report on Accelerator Applications in Europe (112 pages):

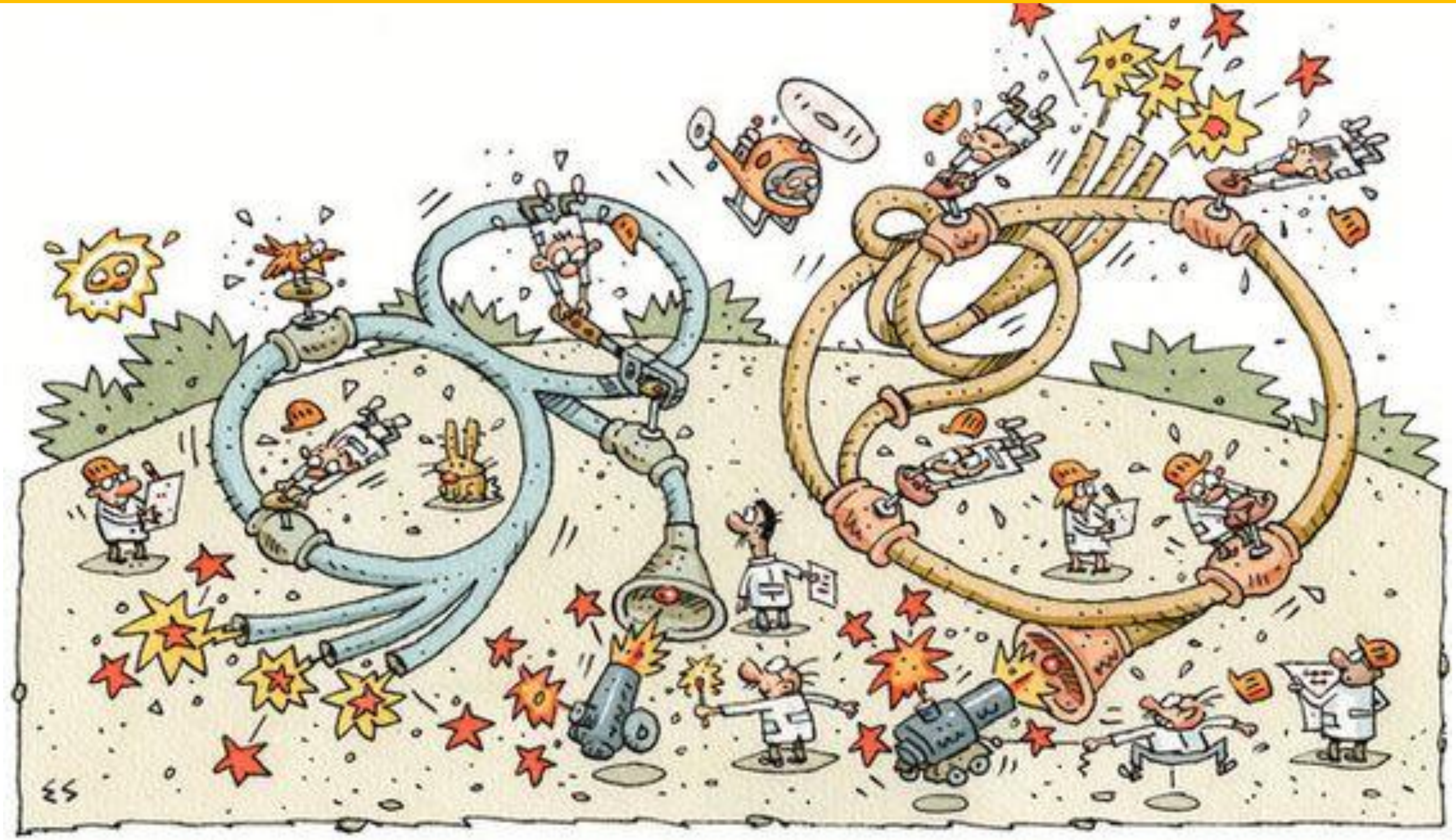
*http://apae.ific.uv.es/apae/wp-content/uploads/2015/04/EuCARD_Applications-of-Accelerators-2017.pdf*

Other useful resources are:

The TIARA site on accelerators for society:
http://www.accelerators-for-society.org/

The US action on Accelerators for America’s future:
http://www.acceleratorsamerica.org/report/index.html

# End of Lecture 7



*DISCLAIMERS:*

*Accelerators for medicine will be the subject of Lecture 8*

*Synchrotron light sources, another important application, have been covered by another lecturer*

Elwood
Smith