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Helmholtz Graduate School for Hadron and Ion Research

CERN

Module 8
Applications of linacs

Overview

Linac applications beyond the usual fields of:

- Injectors for synchrotrons (usually for particle physics)
- Stand-alone accelerators for nuclear physics;

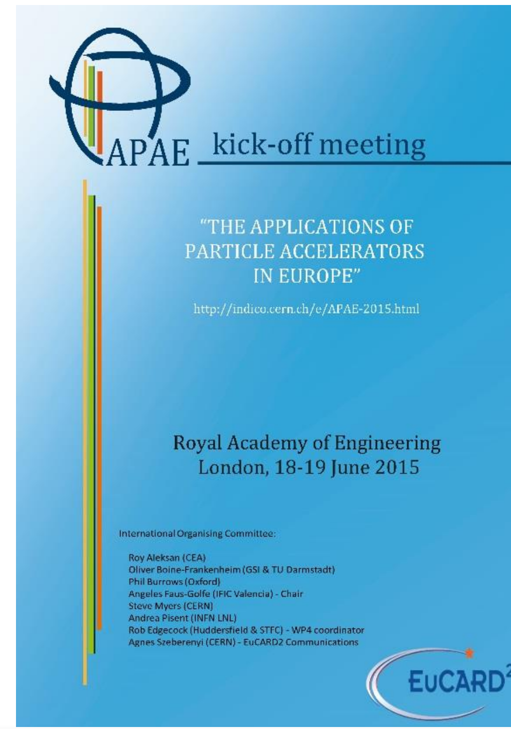
In particular:

1. Applications of High-Power Proton Accelerators (neutron science, energy production, fusion material testing, new physics applications)
2. Industrial and Medical applications

Key questions: what does the man in the street need?

More and better science – we all agree!
More and better life – we all agree, too…

WP4 Accelerator applications



People in the street need the LHC (and now the FCC…) but need as well more and better medical isotopes, better materials, better semiconductors, improved security, etc.

June 2015: Kick-off meeting of APAE: document for policy-makers on applications of interest in Europe and for which technology developed for research can have an impact.

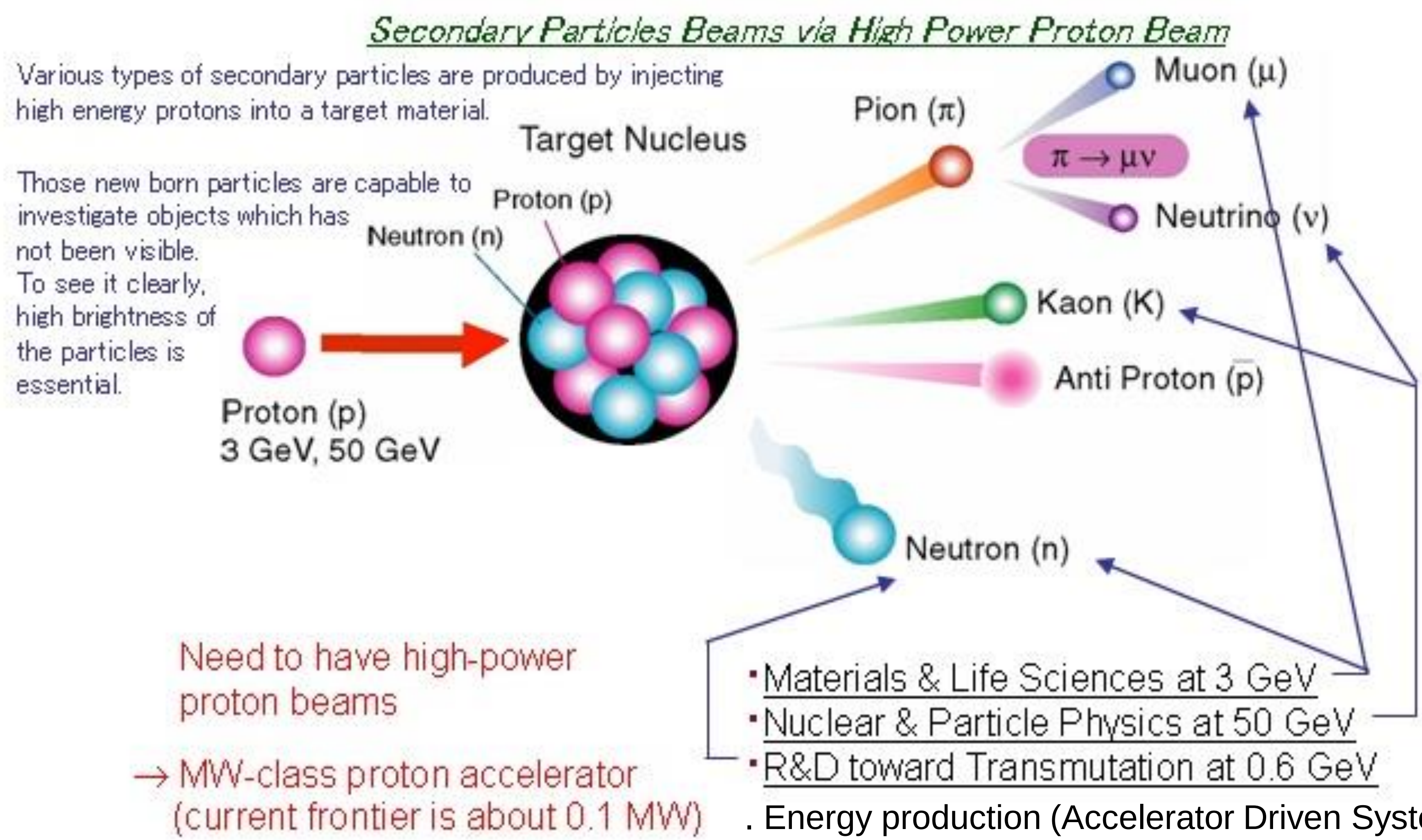
Existing accelerators

~30'000 !

Recherche		**6%**
	Physique des particules	0,5%
	Physique nucléaire, de l'état solide, des matériaux	0,2 a 0,9%
	biologie	5%
Applications médicales		**35%**
	Diagnostic/traitement par X ou électrons	33%
	Production de radio-isotopes	2%
	Traitement par protons et ions	0,1%
Applications industrielles		**60%**
	Implantation d'ions	34%
	Découpage et soudure par électrons	16%
	Polymérisation, …	7%
	Traitement par neutrons	3.5%
	Tests non destructifs	2,3%

Linacs for production of intense secondary particle beams for applied science and energy

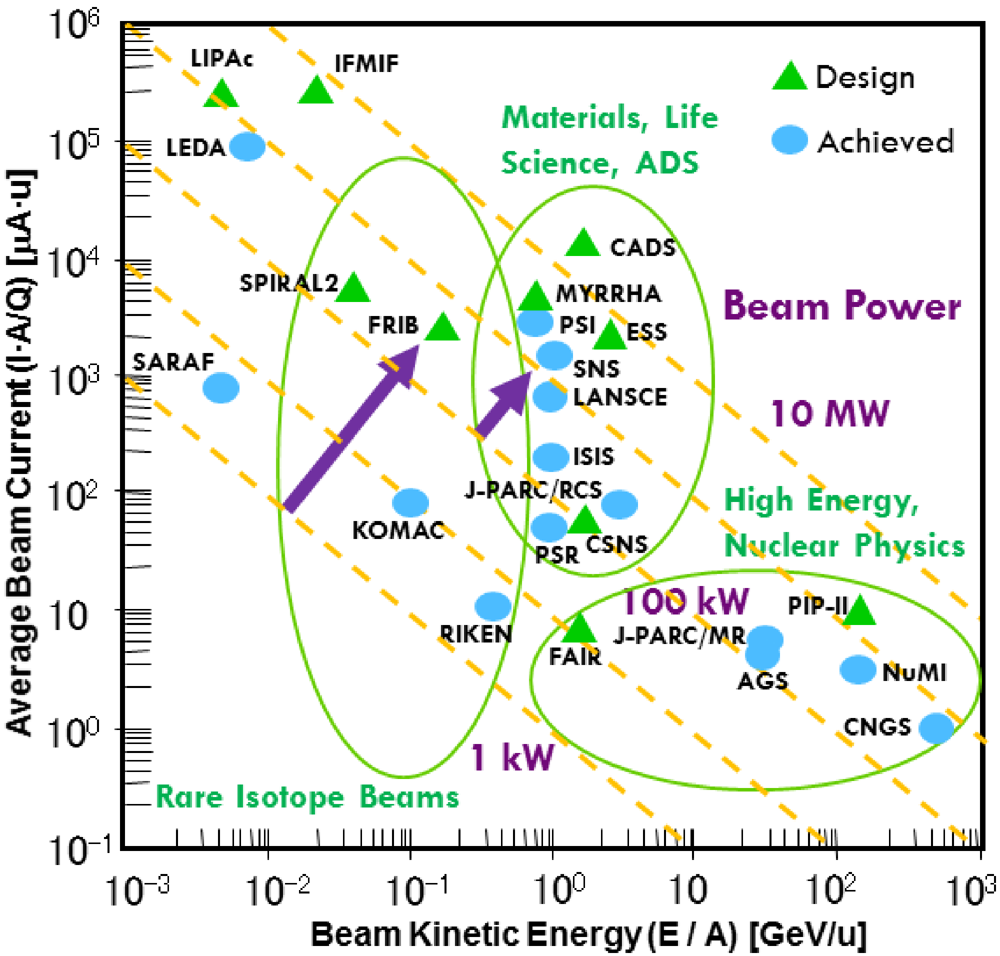
Secondary particle beams



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

(courtesy of JPARC)

Beam power



Jie Wei, IPAC 2014

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

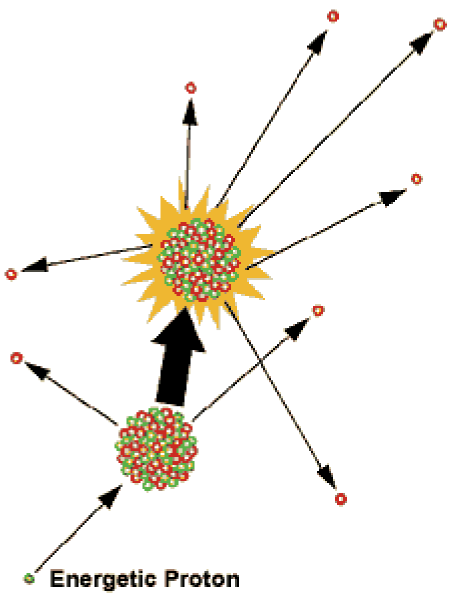
Production rate (cross-section) for most of the particles in high-intensity applications is independent on the energy (above a certain threshold) but proportional to beam power.

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.

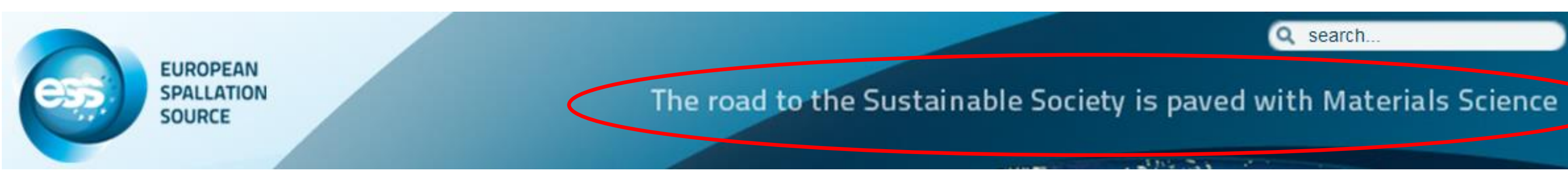
Neutron scattering: Spallation Neutron Sources

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, ...

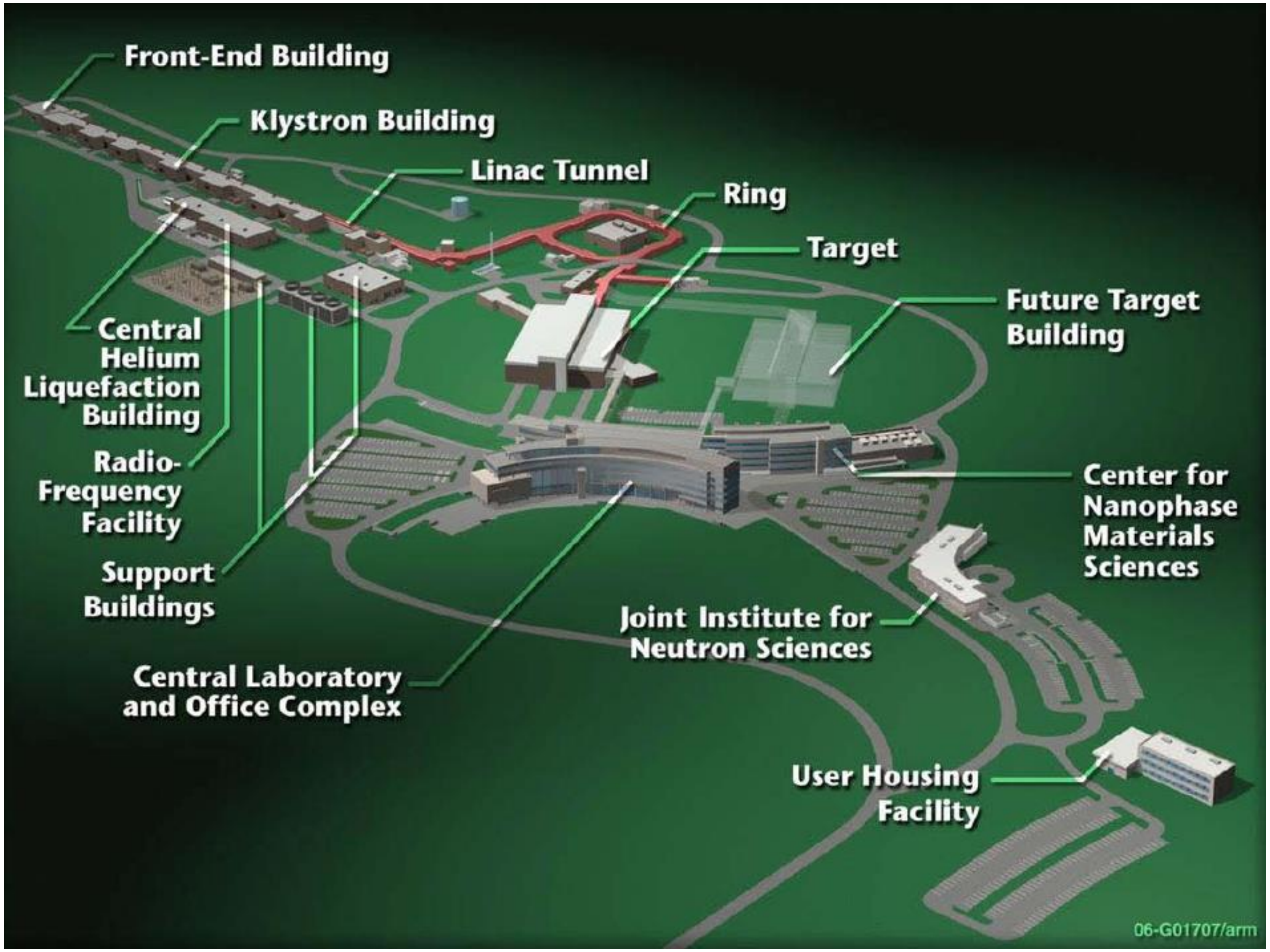


Traditionally, neutrons were produced by nuclear reactors; nowadays, are used linear accelerators at energy ≥ 1 GeV

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).



US Spallation Neutron Source



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

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SNS - layout

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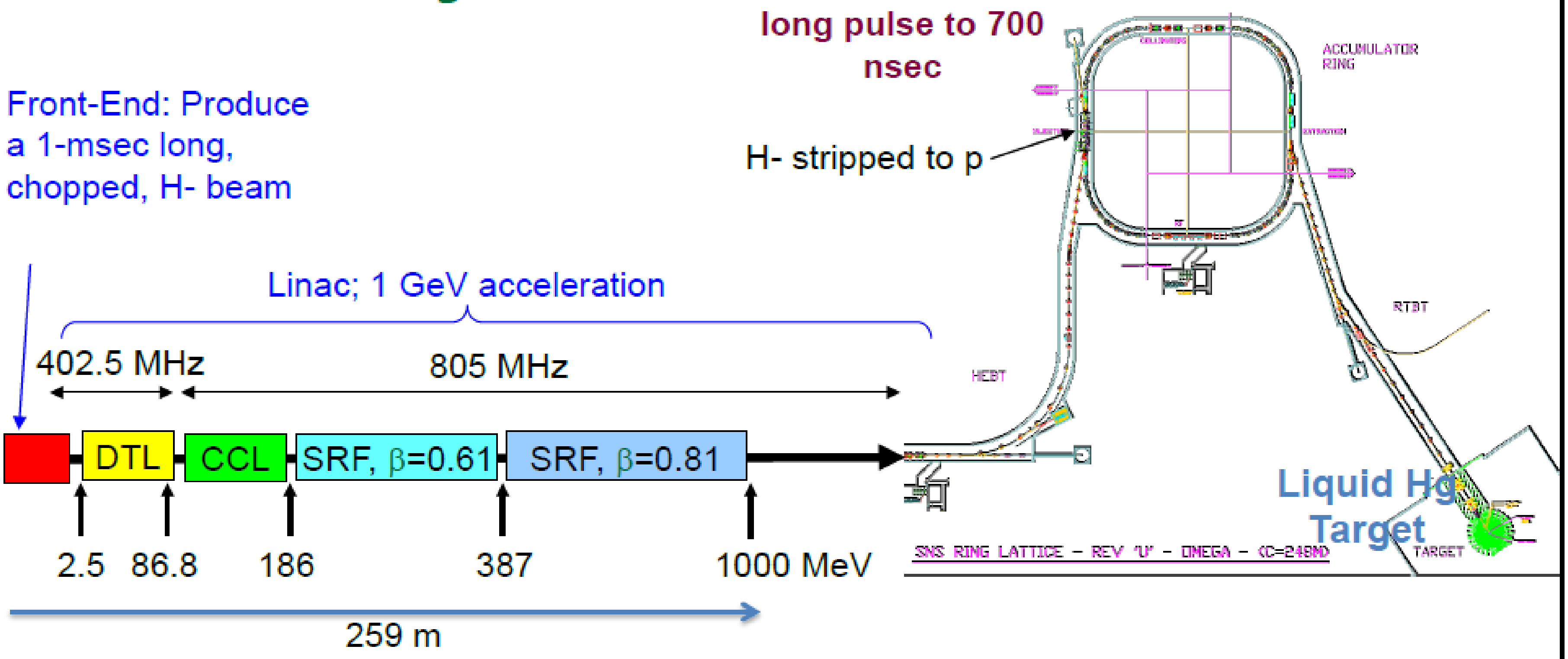
Machine layout

Accumulator Ring: Compress 1 msec long pulse to 700 nsec

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



SNS - Scientific Program

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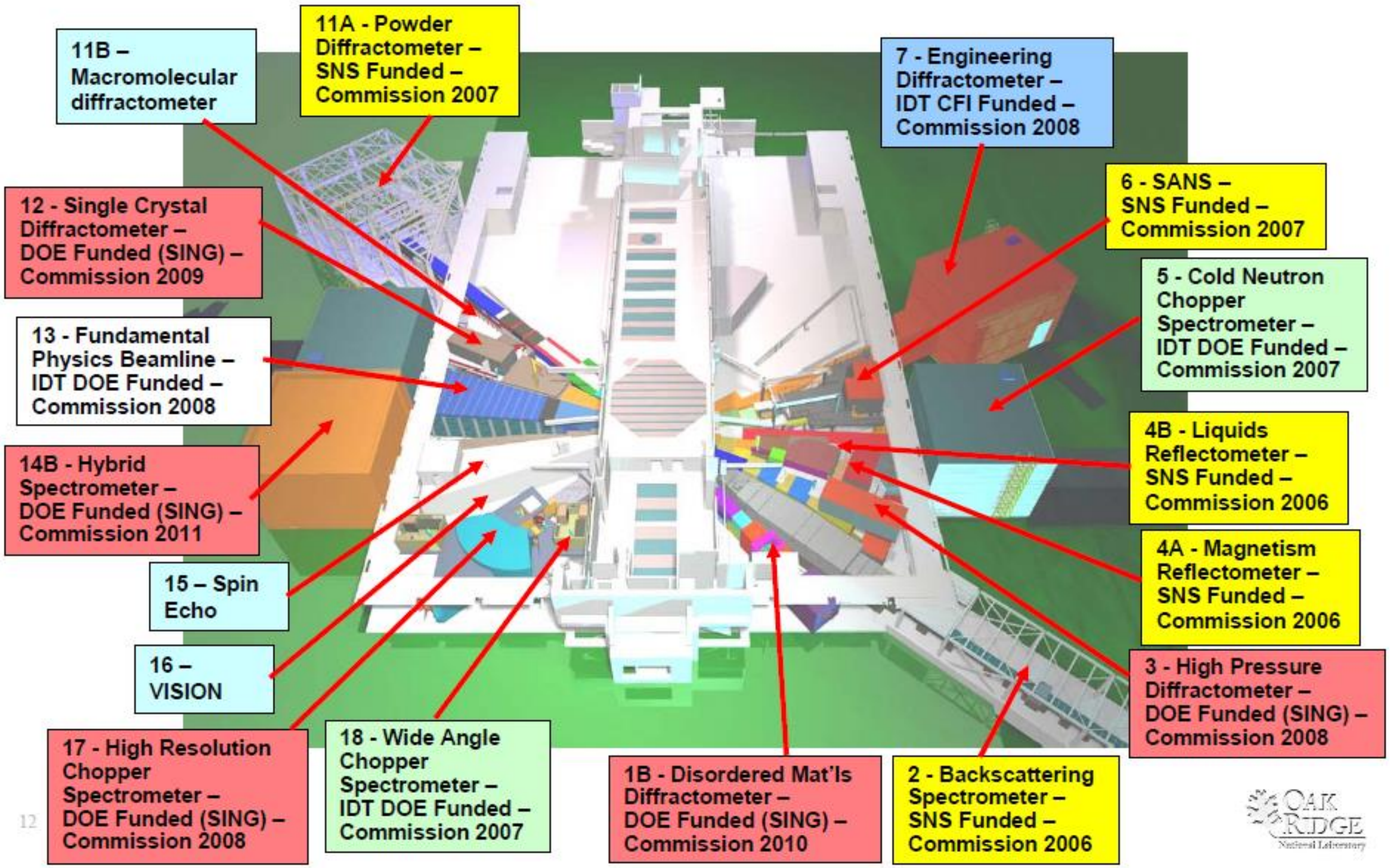
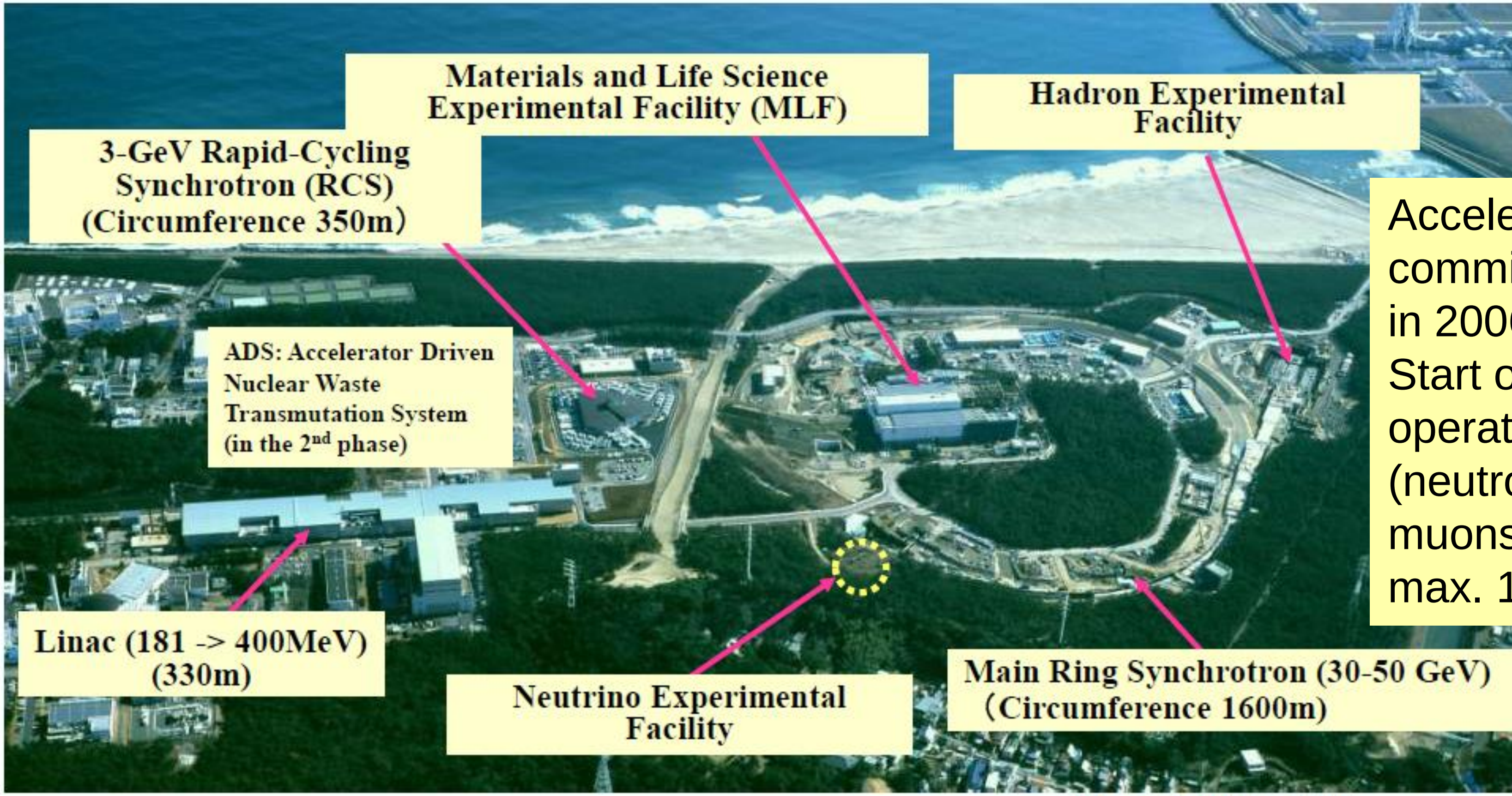
Neutron Instruments

13 are in operation, 3 more will be in 2012



OAK RIDGE National Laboratory

A multi-purpose facility: JPARC (Japan)



Accelerator commissioned in 2006/07. Start of user operation (neutrons and muons) in 2008, max. 120 kW.

Photo in Feb. 2006

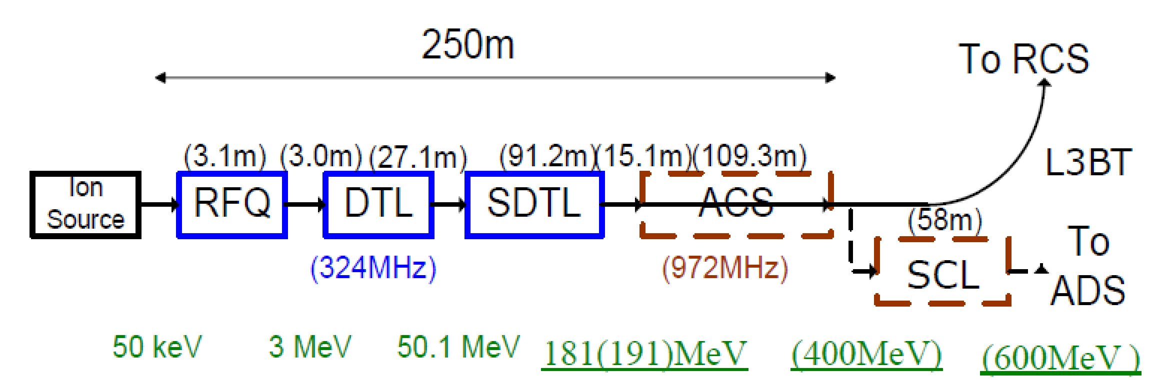
Multi-Purpose Facility

Joint Project between KEK and JAEA

JPARC main parameters

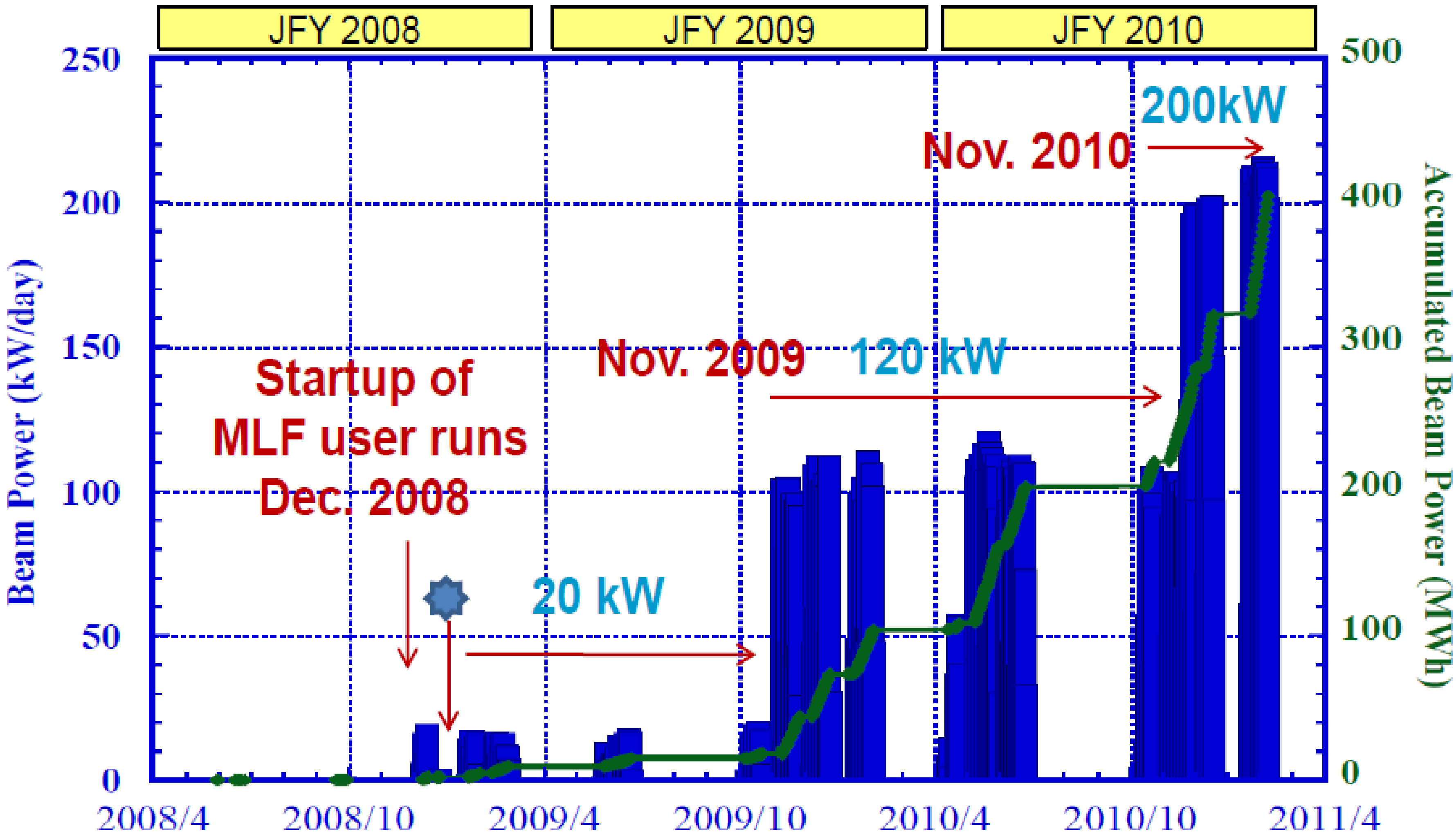
Major Parameters

- Particles: H⁻ (negative hydrogen)
- Energy: 181 MeV, The last two SDTLs are used as debunchers. (400 MeV for ACS, 600 MeV for SCL)
- Peak current: 30 mA (50 mA for 1MW at 3GeV-> Ion source, RFQ)
- Repetition: 25 Hz (additional 25 Hz for ADS application)
- Pulse width: 0.5 msec



Block Diagram of the Linac

Beam Power (3GeV)



European Spallation Source

The ESS is beingbuilt in Lund (Sweden).

Will provide the EU neutron science community with a modern facility replacing the old reactor-based ILL in Grenoble (France).

Expect to complete construction in 2025.

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).

Update from the ESS site

Accelerator technical performances

Design Drivers:

High Average Beam Power

5 MW

High Peak Beam Power

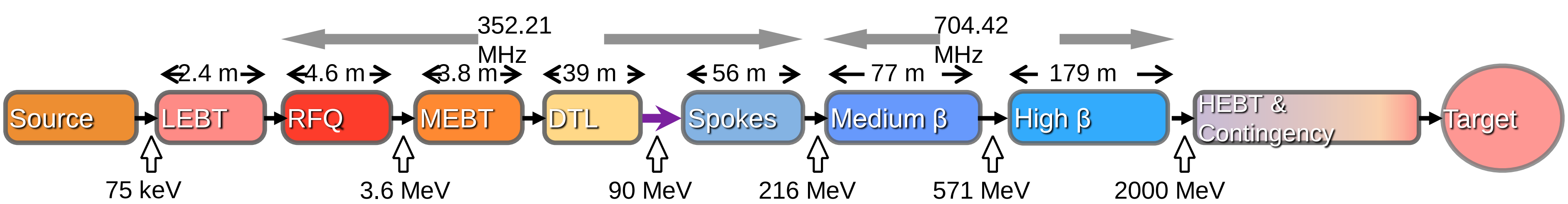
125 MW

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**



ESS Energy Management

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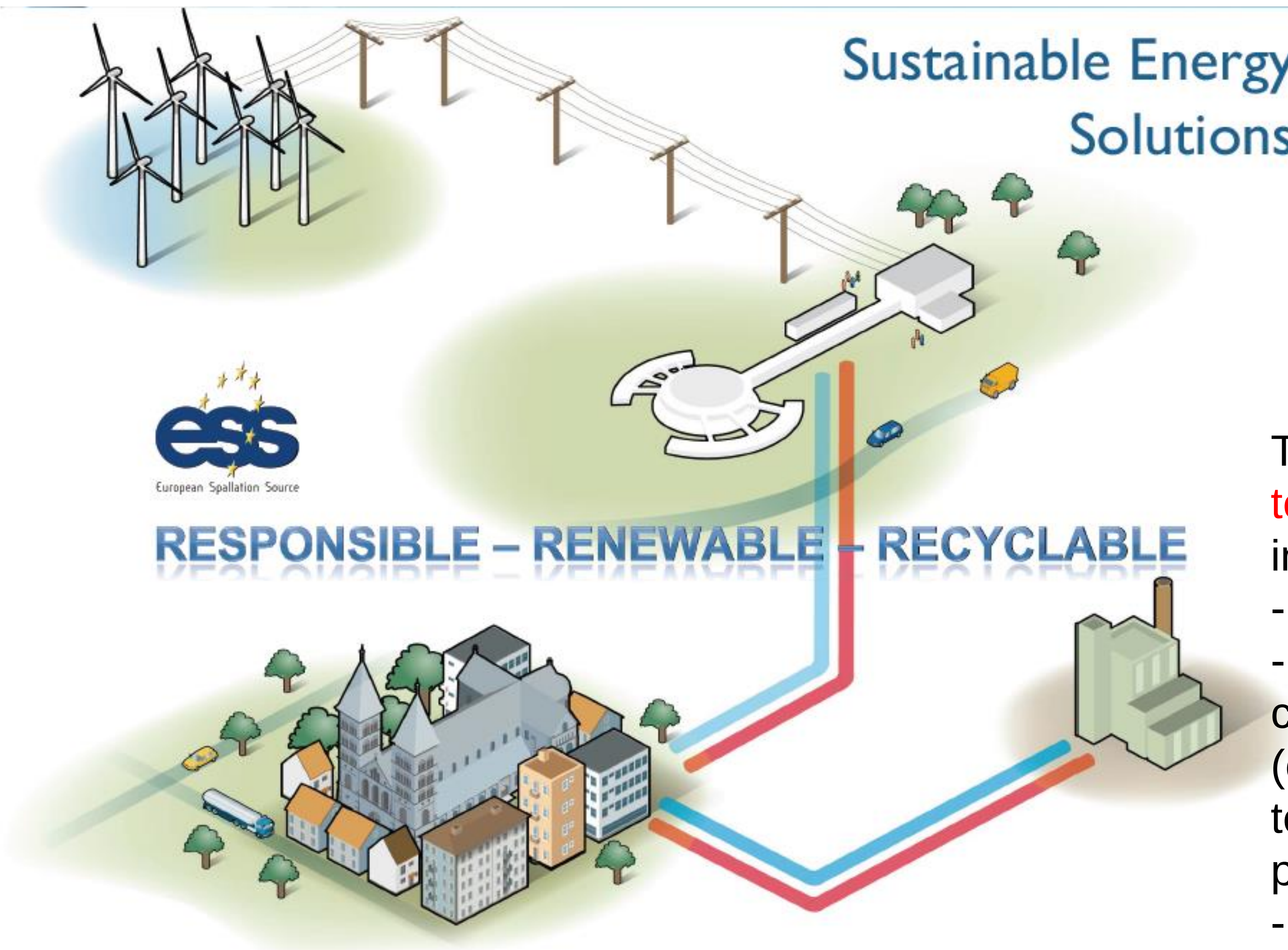


Modern facilities like the ESS need to be "green", to be accepted socially and politically and to prepare for a sustainable future.

⇩

This is an important technical challenge involving:

-Higher efficiency RF;

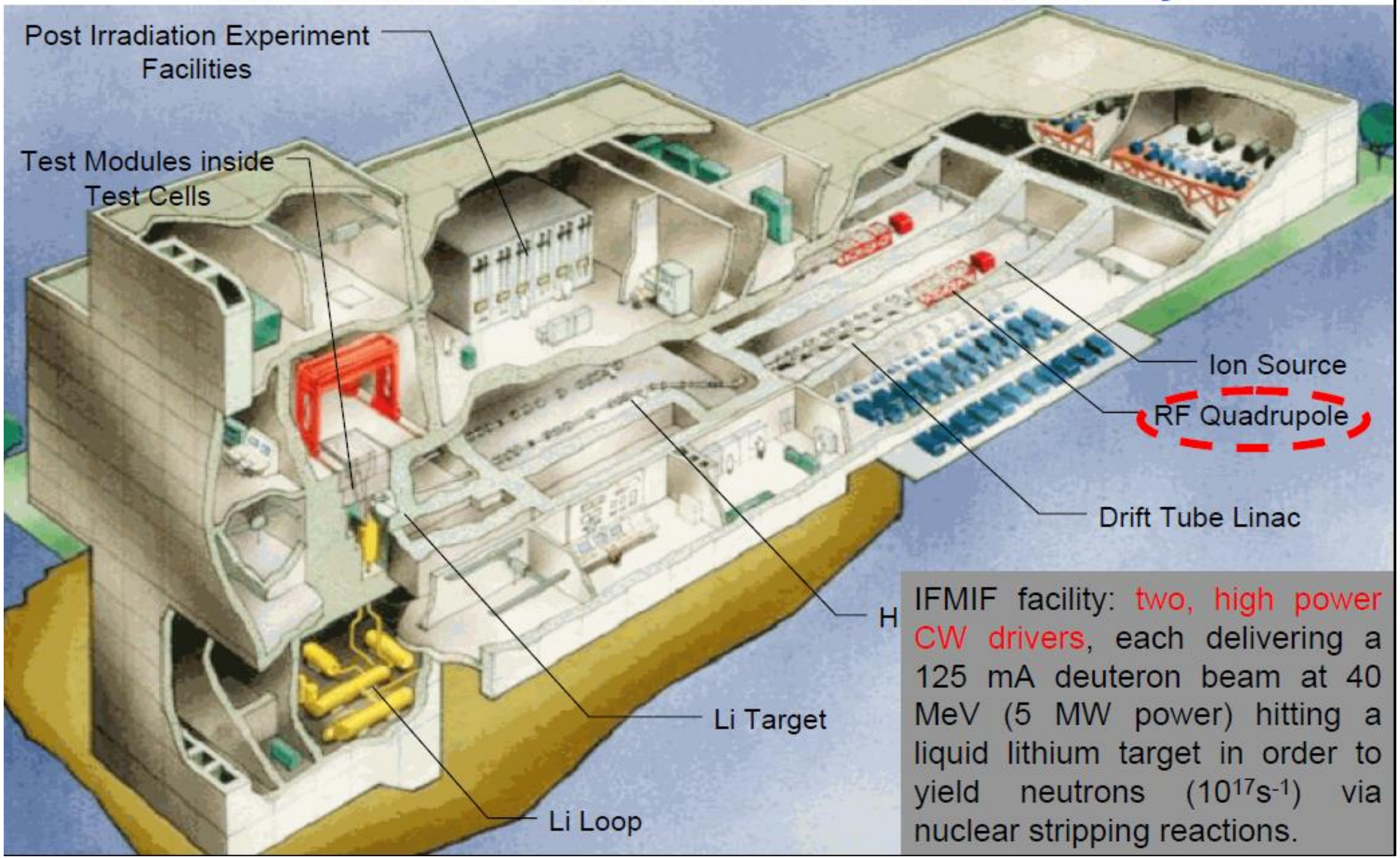
-Recuperation of cooling water (operation at higher temperature and pressure);

-More PMQ-based beam transport

Linacs for fusion material testing: IFMIF

IFMIF "Artist View"

International Fusion Material Irradiation Facility



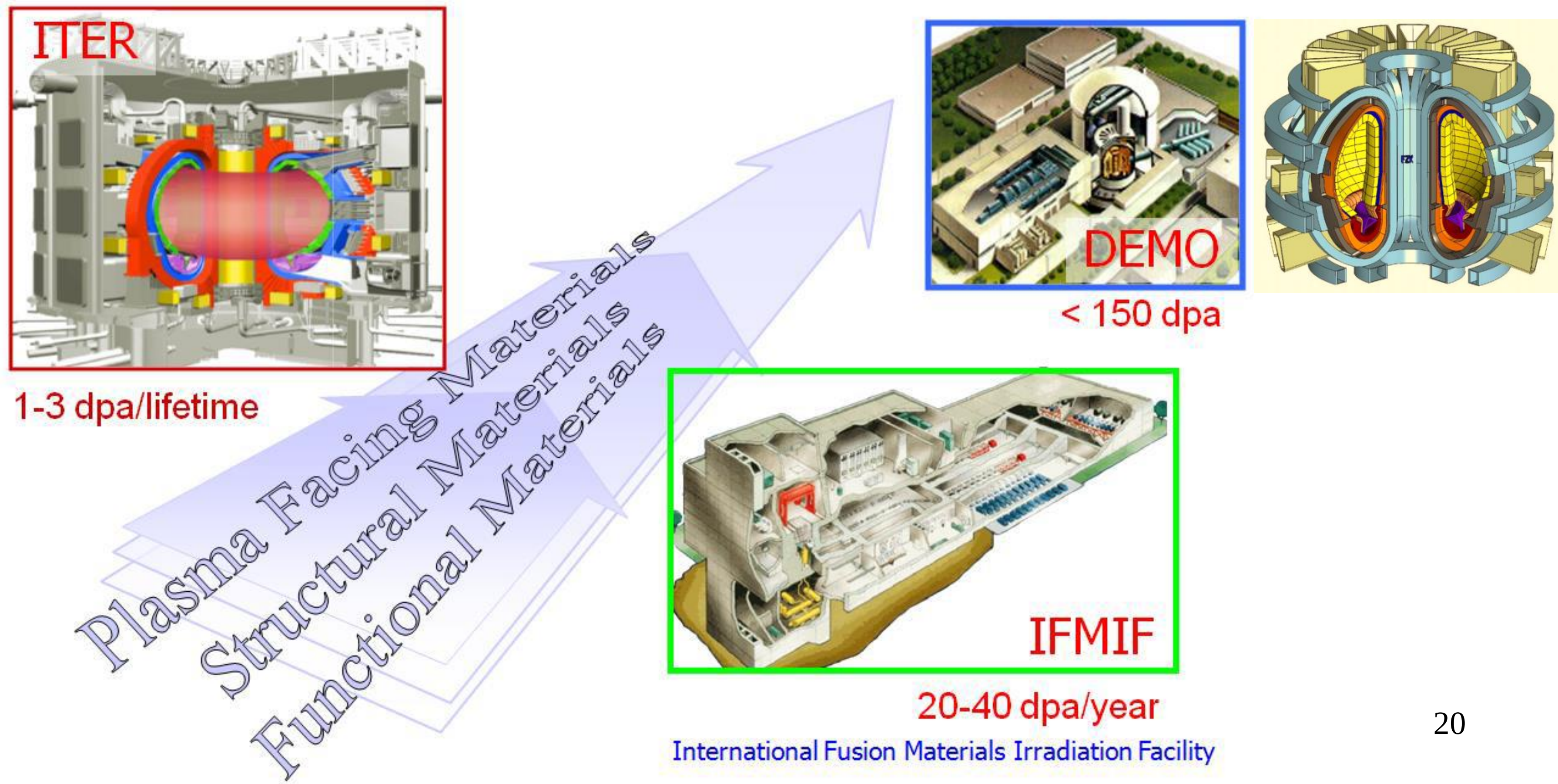
Test under strong neutron fluxes of materials to be used in ITER

Advanced materials on the critical path to fusion

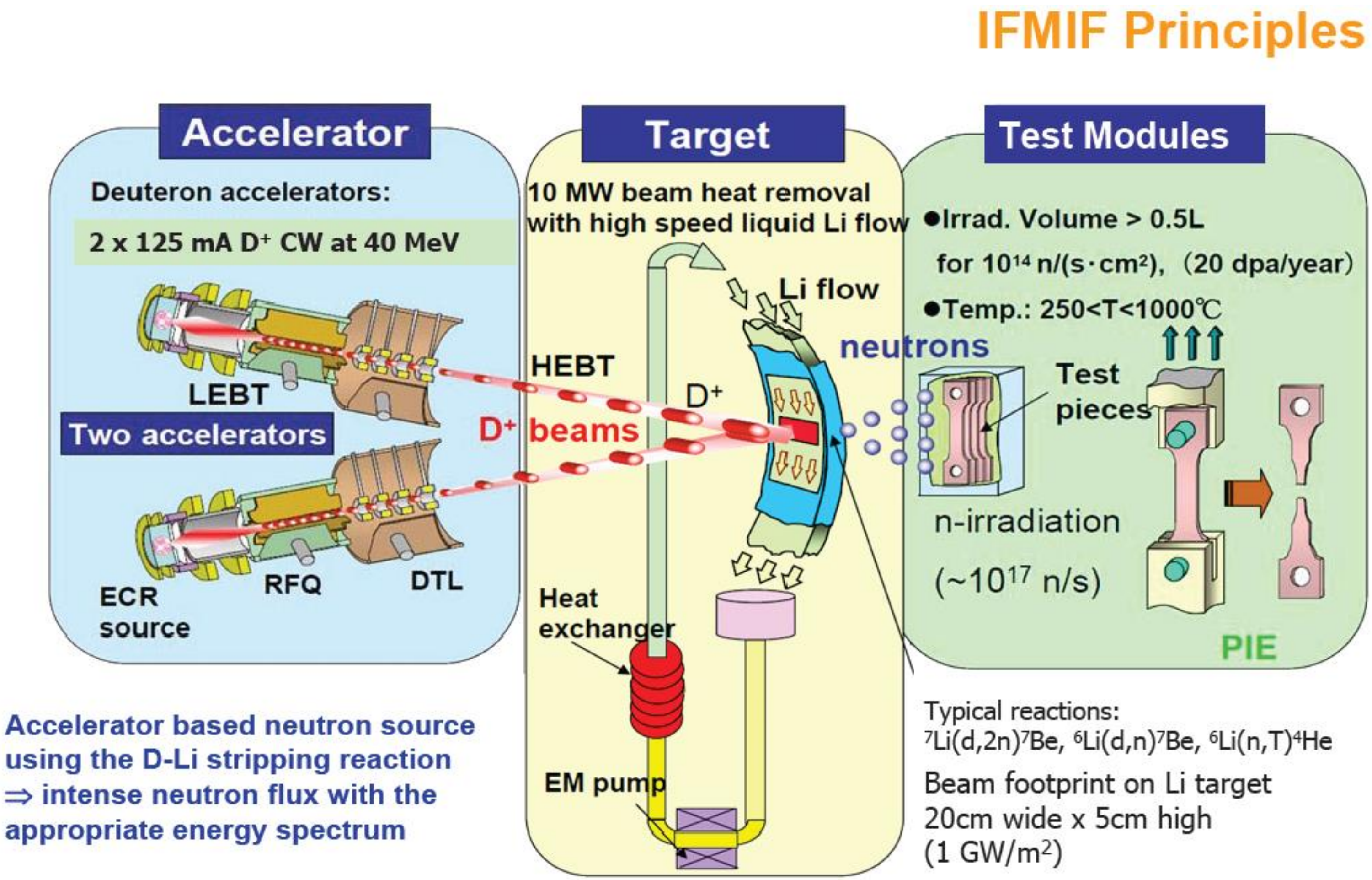
DEMO = Fusion Power Plant Demonstrator (after ITER)

Fusion Power: 2.5 GW (x 5 ITER)

Reactor Efficiency: 37-45%

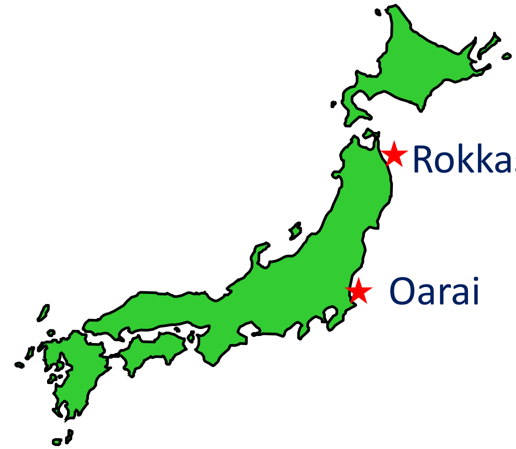


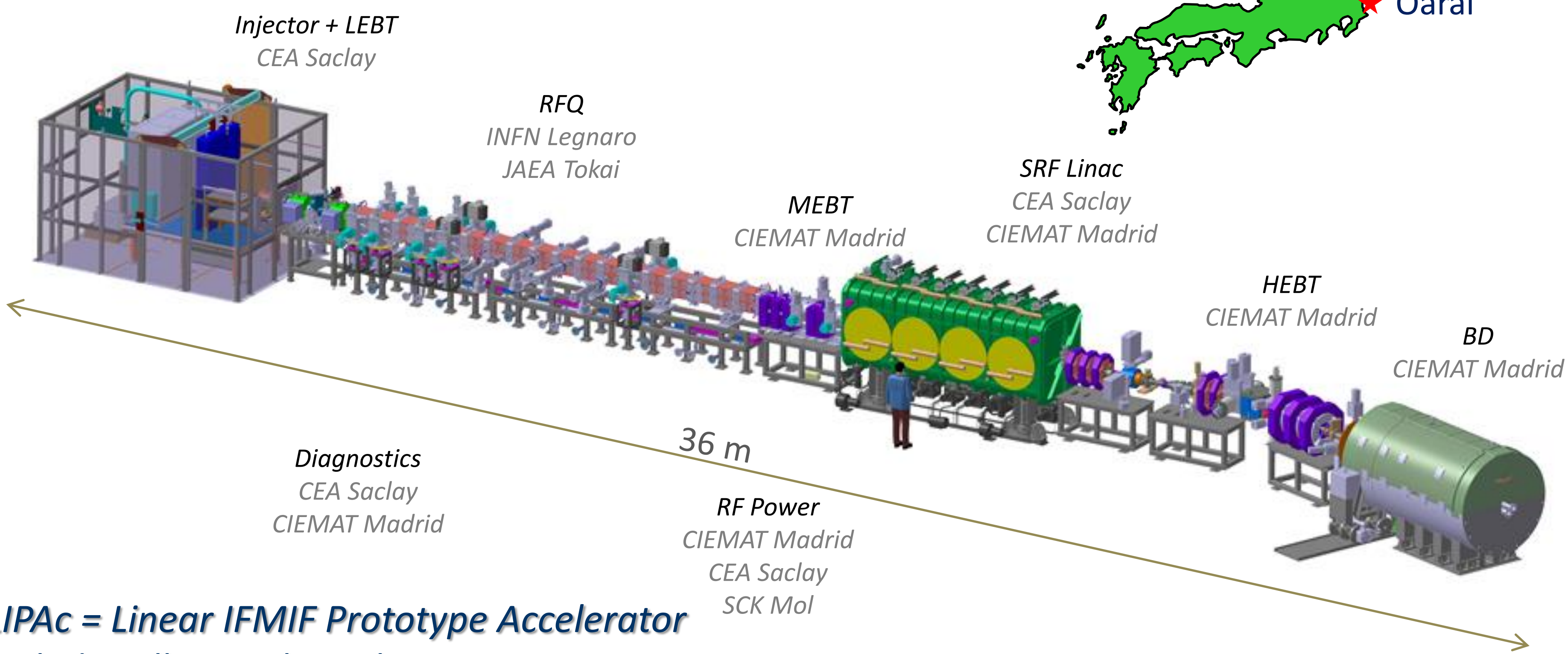
IFMIF principles



LIPAc in construction

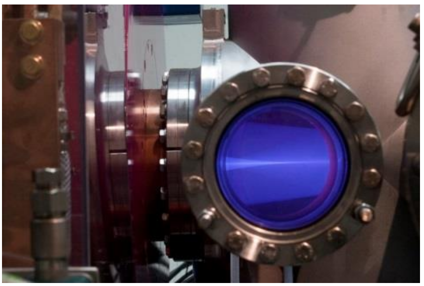
Equipment designed (finished)
and constructed in Europe
Installed and commissioned in Rokkasho

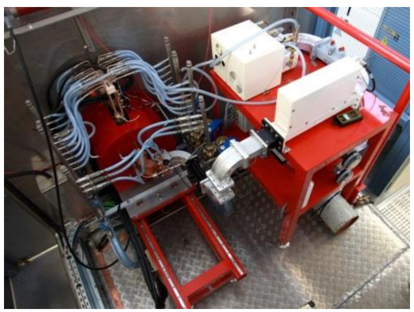




LIPAc = Linear IFMIF Prototype Accelerator
includes all critical accelerator components
to be tested at nominal beam current at BA site

Injector (CEA, Saclay)





D⁺ (95% species fraction)

Ion Source ECR (2.45 GHz) - CW

E = 100 keV

I = 140 mA

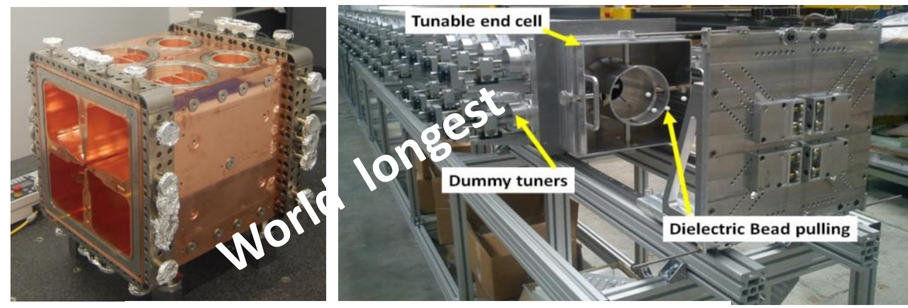
emittance of 0.25 π mm·mrad

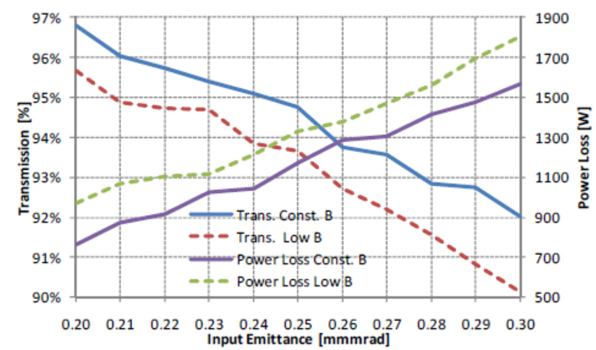
Availability > 95%

Acceptance tests in Saclay successfull

Commissioning in Rokkasho on-going

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)

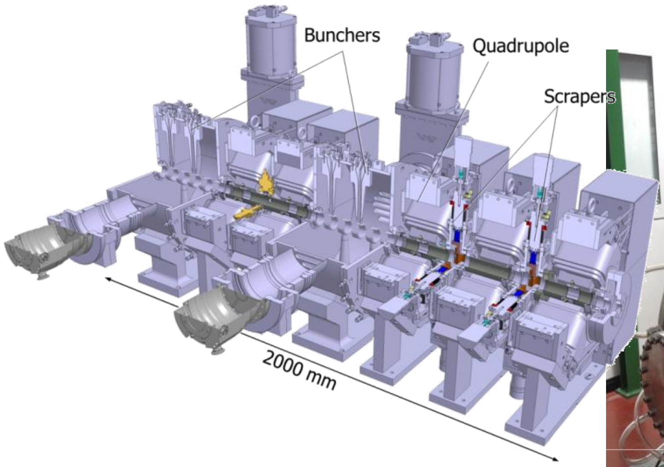
Tuning demonstrated in an Al full scale prototype

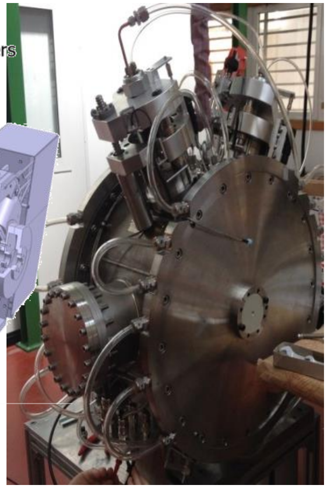
3-module RFQ successfully conditioned

at 178 kW in CW (nominal field)

MEBT (CIEMAT, Madrid)	SRF Cryomodule (CEA, Saclay)

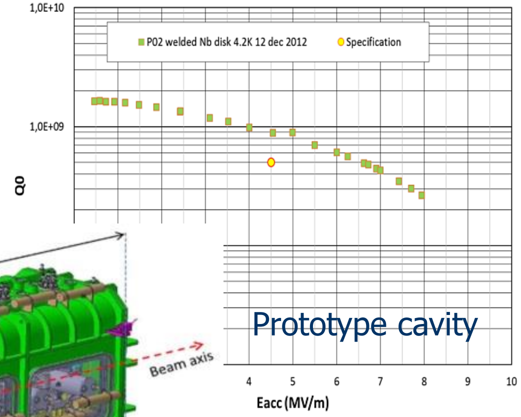
MEBT (CIEMAT, Madrid)

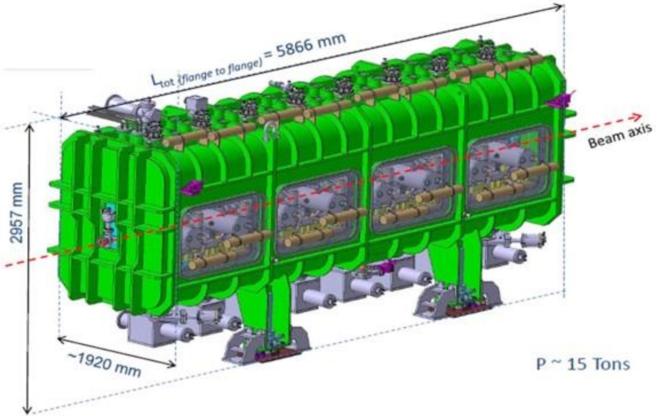




very compact ~ 2 m, many components
5 quadrupoles & steering coils
2 bunchers (5 gaps IH), 2 movable scrapers
BPMs (in the center of quads)
turbomolecular pumps on bunchers
(1300 l/s /buncher)
High Power Test of the Buncher successful
up to CW operation at the target value (350 kV)
Contracts being launched
Assembly in Japan being assessed

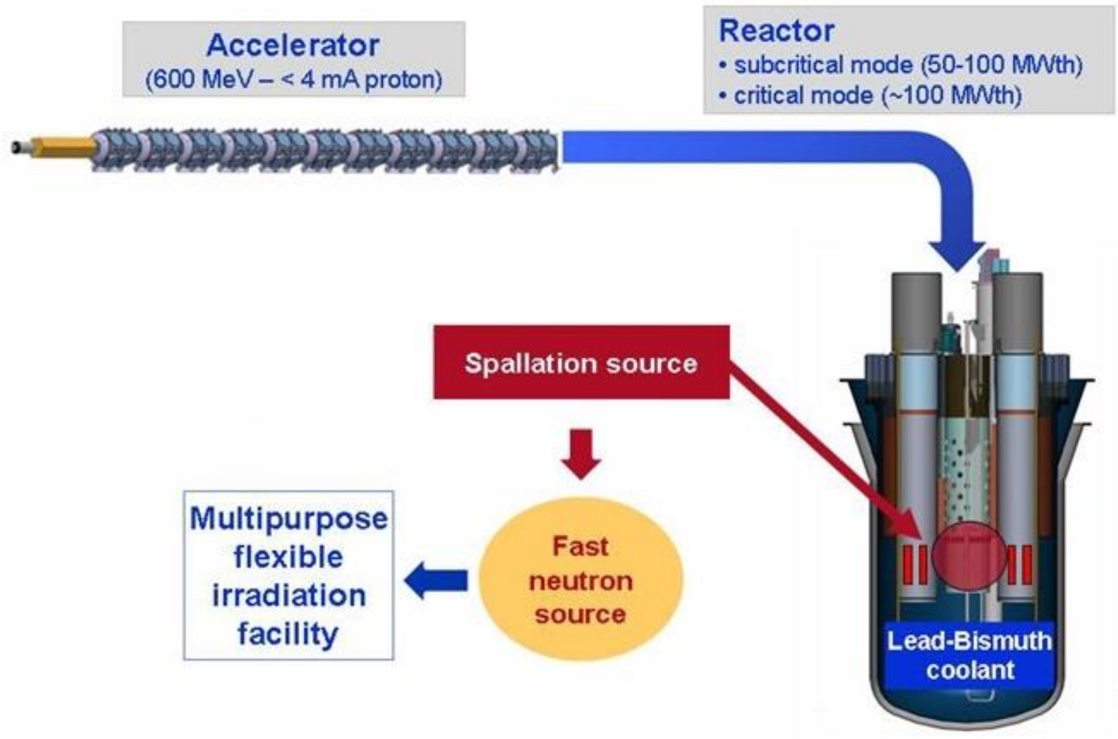
SRF Cryomodule (CEA, Saclay)





8 resonators (β=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
Assembly in Japan being assessed

Accelerator Driven Systems



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

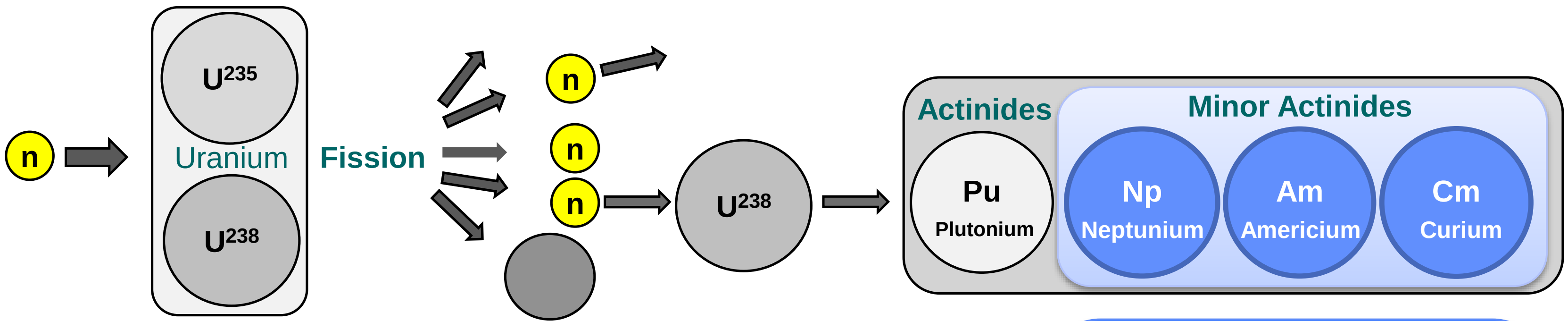
Can be used for a **transmutation facility** processing long-life nuclear waste and transforming it into shorter lifetime waste.

In addition, it could be used for energy production allowing **alternative fuel cycles** (thorium) and with no safety concerns (subcritical).

The MYRRHA Project (Multi-purpose hYbrid Research Reactor for High-tech Applications) based at Mol (BE) is the European way to an ADS demonstrator: in the ESFRI list, partly supported by EU and by the Belgian government, looking for other international partners.

ADS demonstrator + fast neutron irradiation facility

The transmutation issue



Minor Actinides

- Long lived (>1,000 years)
- Very radiotoxic
- Very hot

The European Strategy for Partitioning & Transmutation: 4 building blocks

- Process a sizable amount of spent fuel from commercial LWRs
  - Separate plutonium (Pu), uranium (U) and minor actinides (MA),
- Fabricate at a semi-industrial level the dedicated fuel
- Design and construction of one or more dedicated transmuters
- Process the dedicated fuel unloaded from the transmuter
  - Fabricate new dedicated fuel

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Energy Production

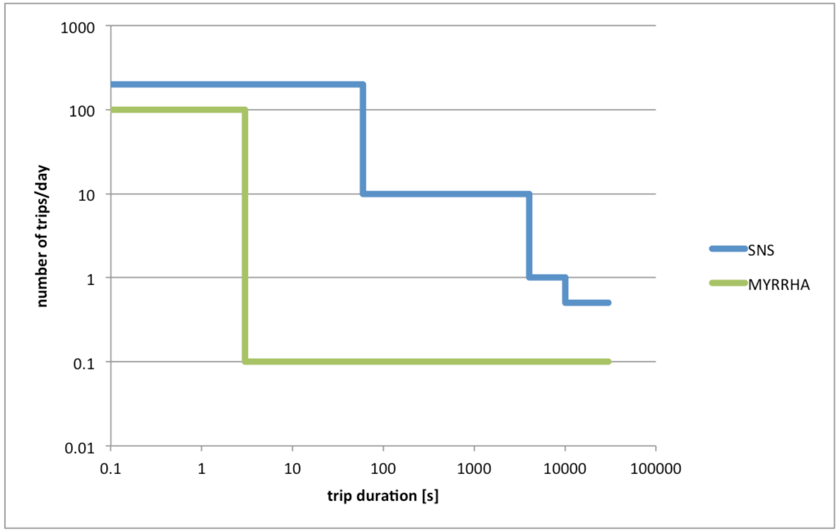
Advantages/disadvantages of accelerator driven systems as compared to conventional reactors:

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)

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 (MYRRHA)



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
   - Possible 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)

EU: The Myrrha project

MYRRHA Project

Multi-purpose hYbrid Research Reactor for High-tech Applications at Mol (BE)

Development, construction & commissioning of a new large fast neutron research infrastructure to be operational in 2023

❶ ADS demonstrator

❷ Fast neutron irradiation facility

❸ Pilot plant for LFR technology

Main features of the ADS demo

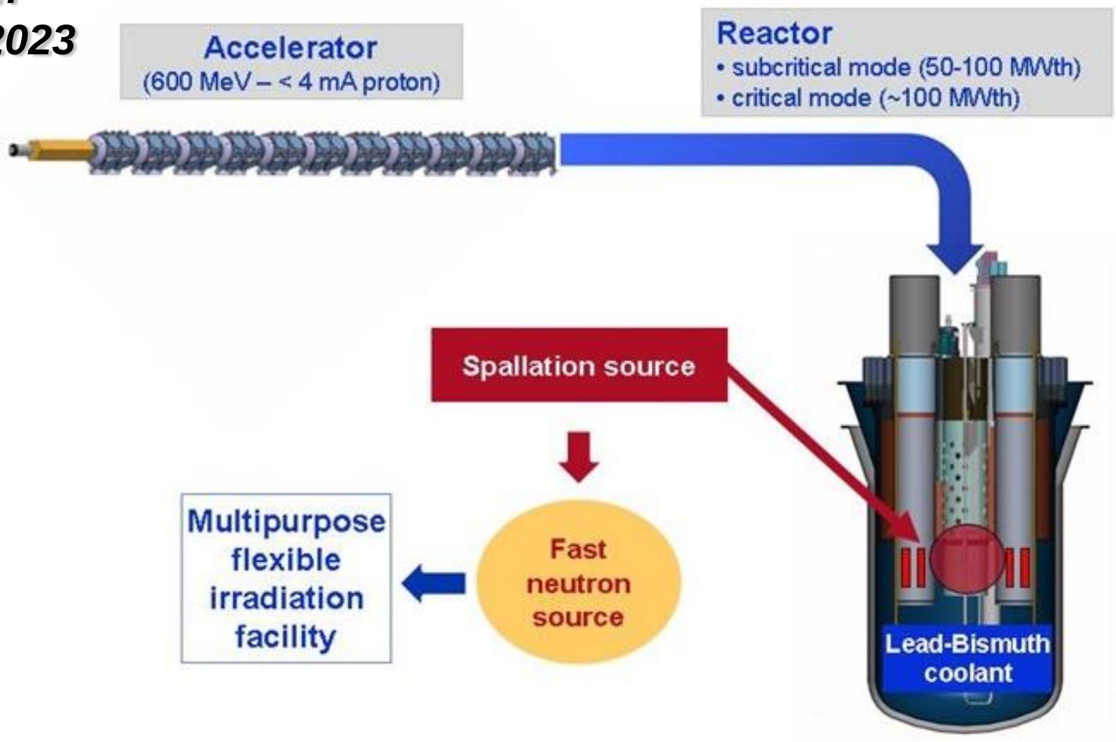
50-100 MWth power

k_{eff} around 0.95

600 MeV, 2.5 - 4 mA proton beam

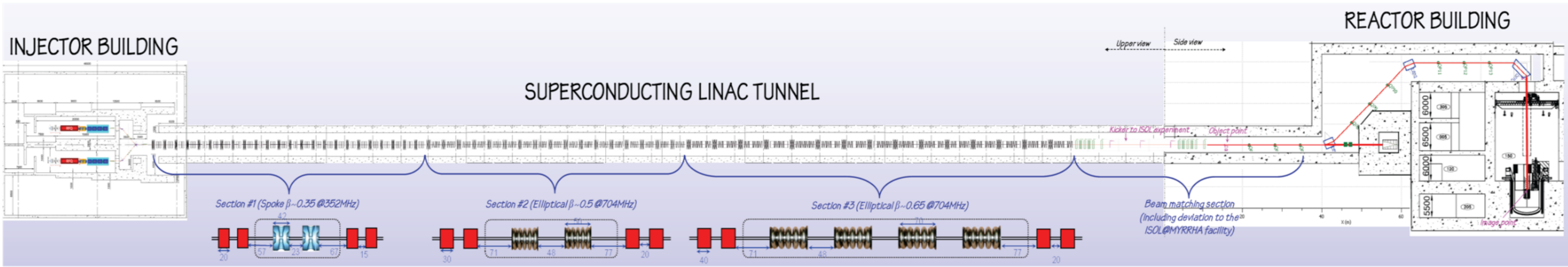
Highly-enriched MOX fuel

Pb-Bi Eutectic coolant & target



- **2010: MYRRHA is on the ESFRI list, and is officially supported by the Belgium government at a 40% level (384M€, w/ 60M€ already engaged)**

The MYRRHA accelerator



Roadmap of ADS project in China

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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

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Industrial applications of linacs

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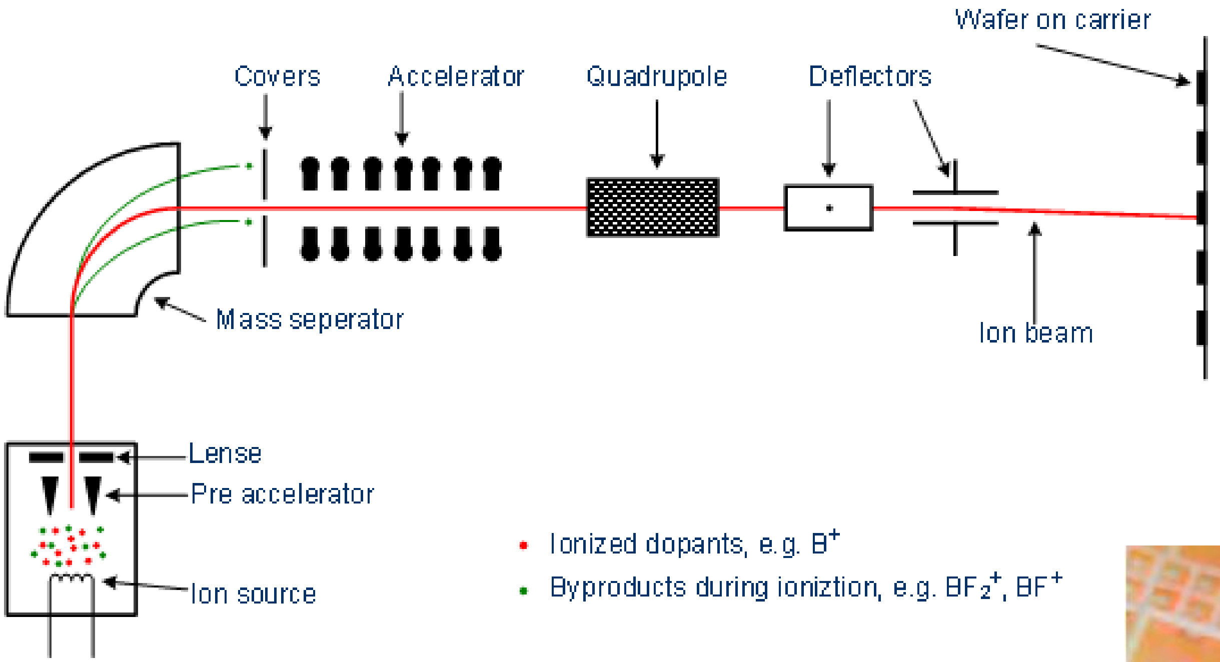
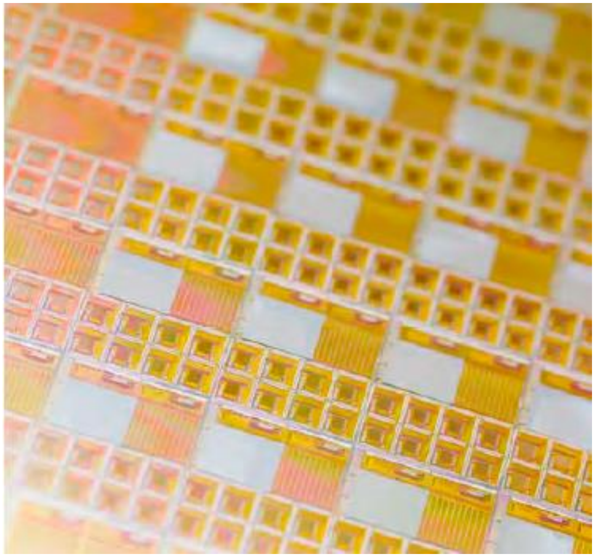
	Goal	Examples	Accelerator
Material processing (electrons)	Improve polymer resins inducing cross-linking of polymer chains → higher stress resistance	Heat-shrinkable films for food packaging, tires and cable insul. Gemstone irradiation	Electrons, 100 keV-10 MeV
Sterilization	Kill microroganisms	Sterilization of medical products Food processing (public acceptance!)	Electrons, ~10 MeV
Wastewater treatment	Distruction of organic compounds	Russia, Korea, USA, Brazil	Electrons, ~10 MeV
Non-destructive testing	Detect discontinuities in a material (cracks, etc.)	Inspection of pipelines, ships, bridges, etc. (depth + variable energy)	Electrons for X-rays, 1-15 MeV, portable (9 GHz)
Cargo inspection	Screening of trucks or containers for illegal objects	Many ports, customs, etc.	Electrons for X-rays, 3-6 MeV
Ion implantation	Alter near-surface properties of semiconductors (doping)	Semiconductor industry (arsenic, boron, indium, phosphorus,…)	Ions, from low to high energy (5 MeV)
PET isotope production	Production of radiotracers for Positron Emission Tomography	Linacs are smaller and have less res. activation than cyclotrons	Protons, 7 MeV
Neutron testing	Neutron generation for non-destructive inspection	Inspection of materials, cargo, etc.	Protons, 1-10 MeV

More than 20’000 industrial linacs in operation in the world.

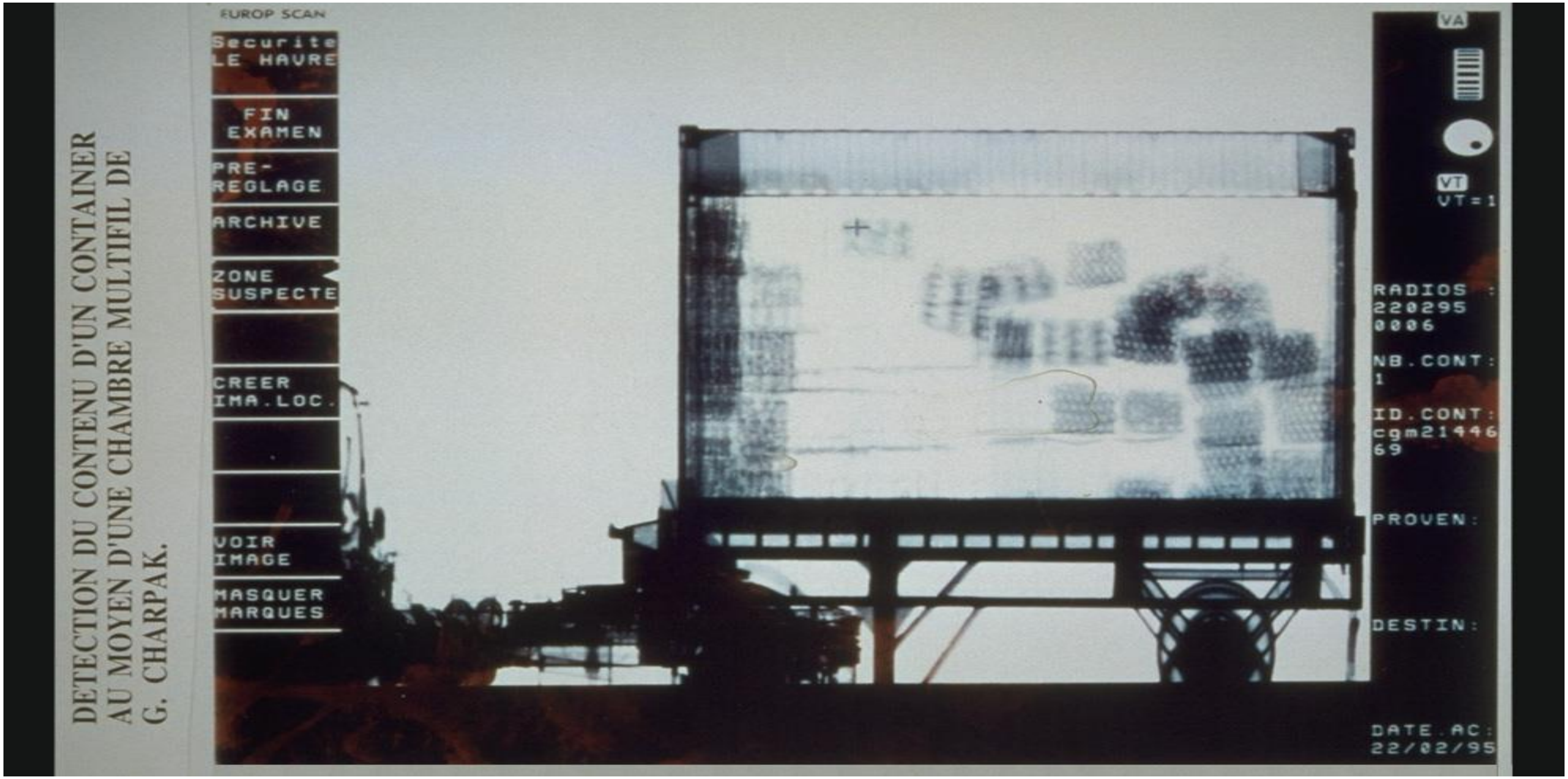
A large fraction is made of small electrostatic machines for ion implantation (10’000 units).

Ion implantation system

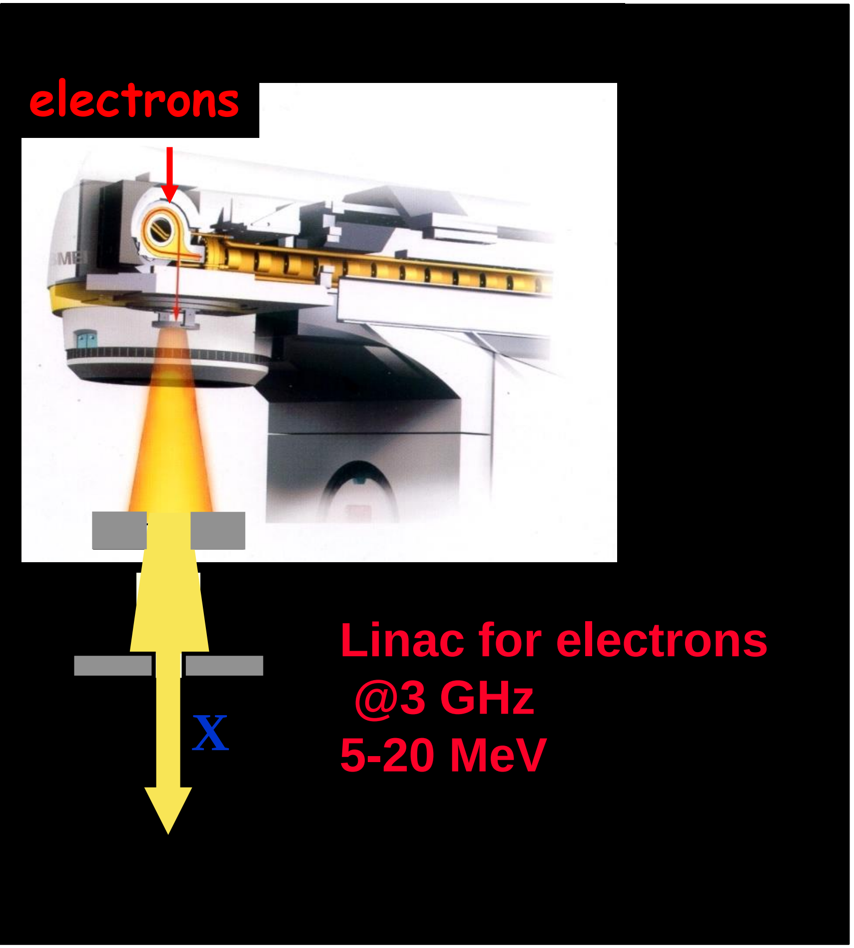


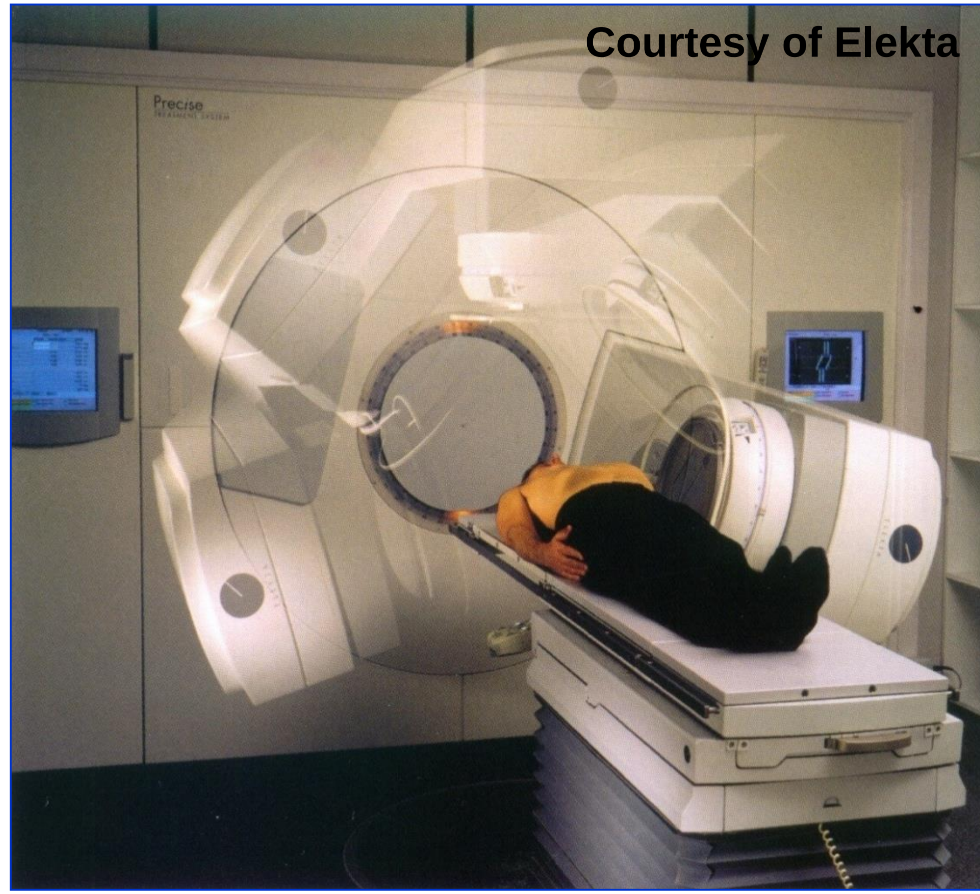


Cargo screening



Radiotherapy with linear accelerators



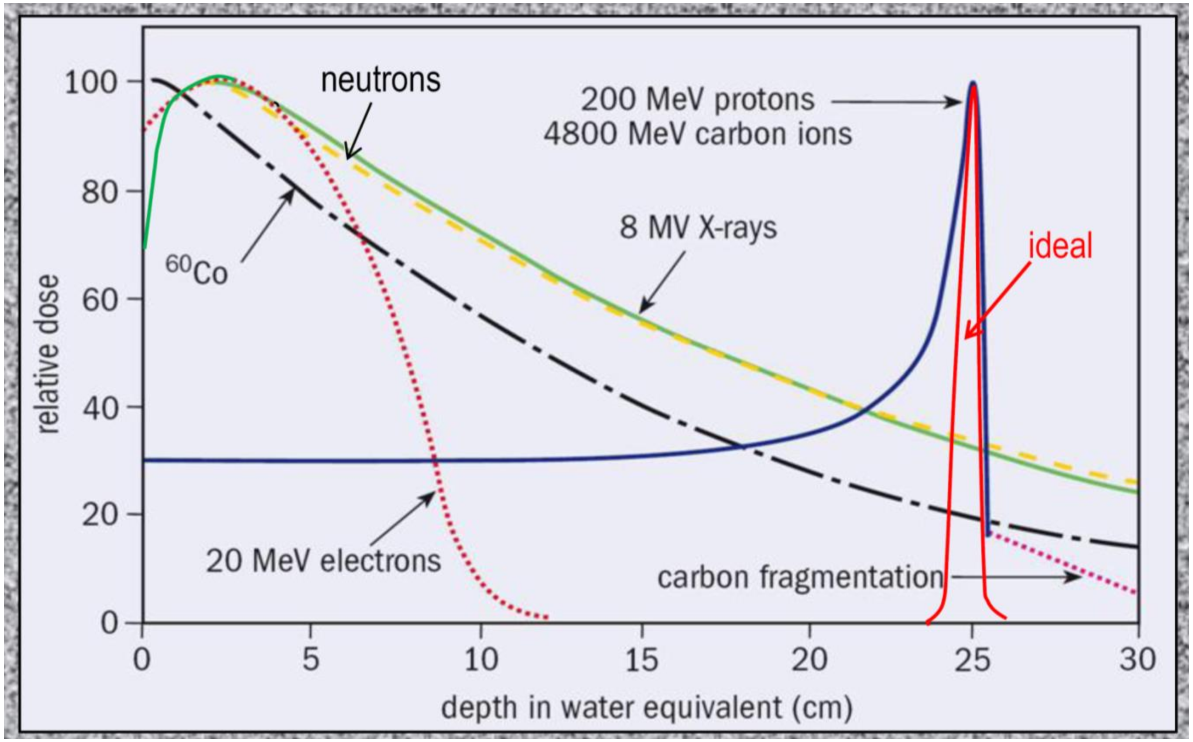


>7000 electron linacs in the world for radiotherapy

20 000 patients per year every 10 million inhabitants

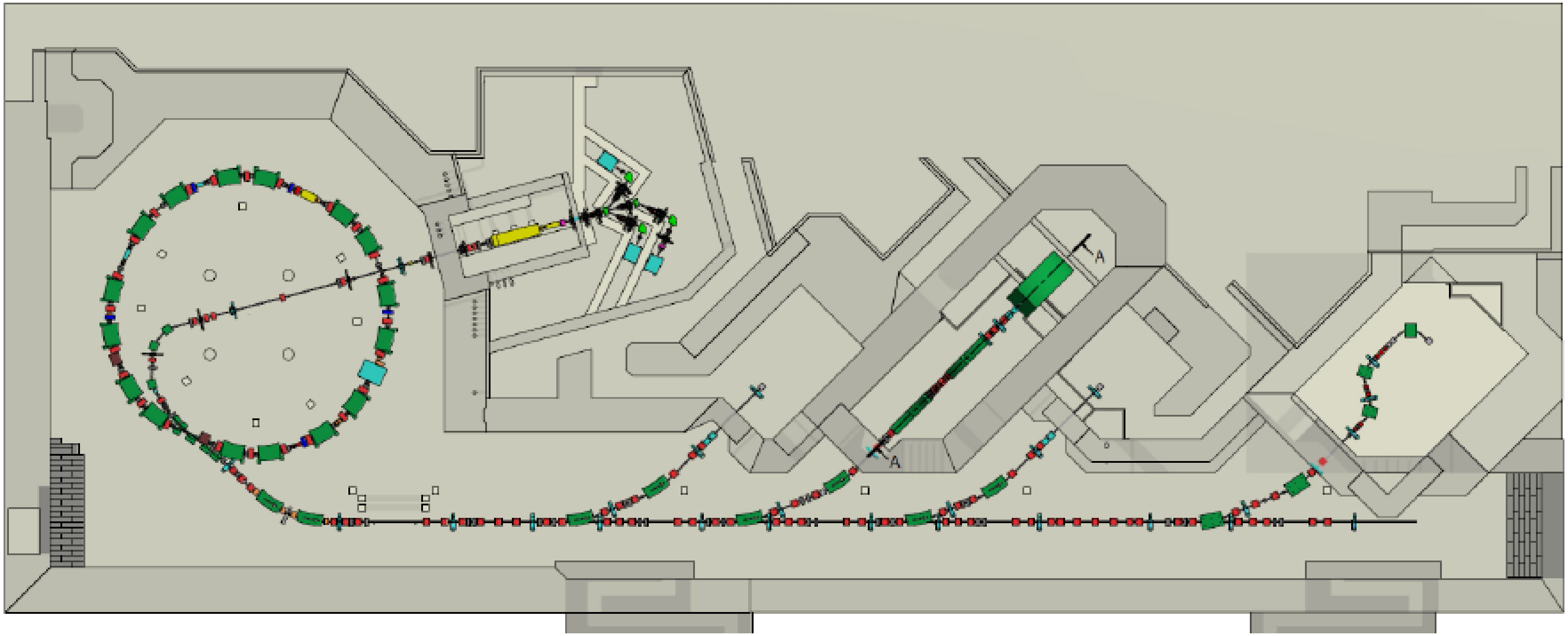
Hadrontherapy

'Hadrontherapy': cancer therapy modalities which irradiate patients with beams of hadrons. The "Bragg peak" allows to concentrate the radiation dose on a deep tumour, minimising the dose to the adjacent tissues.
Hadrontherapy is an alternative to usual irradiation with X-rays from e- linacs.



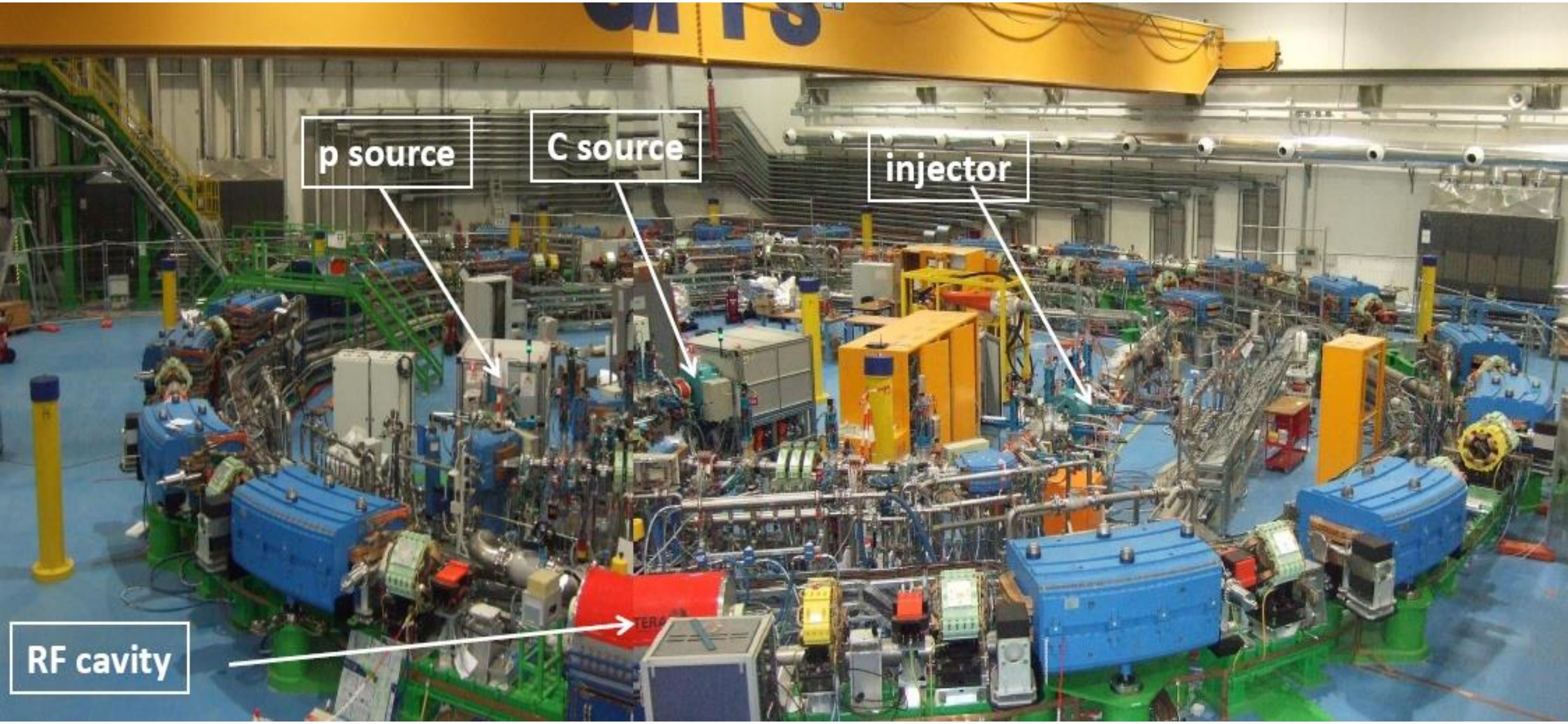
Most used hadrons: protons and carbon ions.
- Protontherapy is rapidly developing: more than 65'000 patients treated, 5 companies offer turn-key solutions.
- Carbon ions, used for about 6000 patients, have a larger radiobiological effectiveness and require more radiobiological and clinical studies to define the best tumour targets.

MedAustron



Recently commissioned at Wiener Neustadt
Linac: protons and carbon ions (2 sources+hot spares), 7 MeV/nucleon, RFQ+IH, 216.8 MHz, stripping after linac

CNAO in Pavia (Italy)

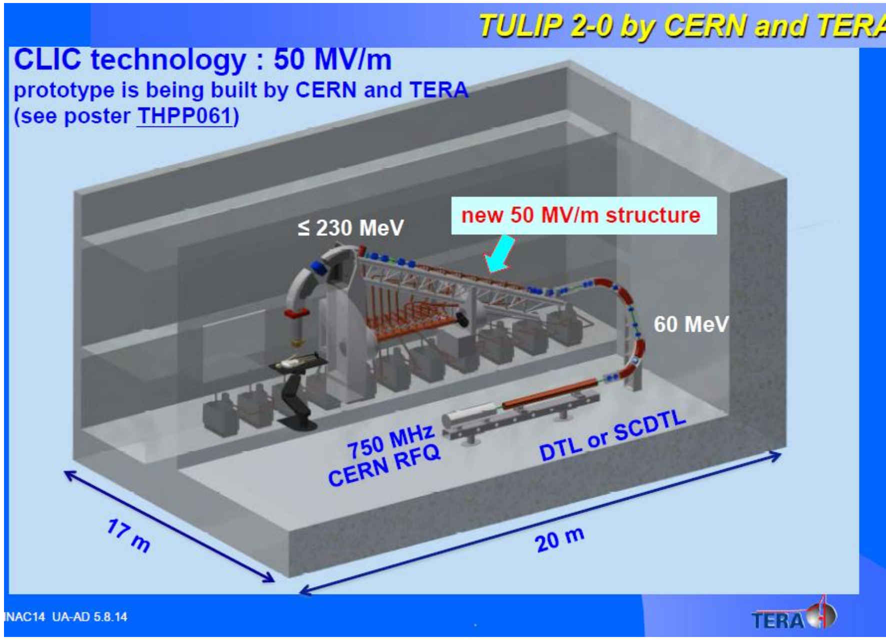


The synchrotron area in October 2008

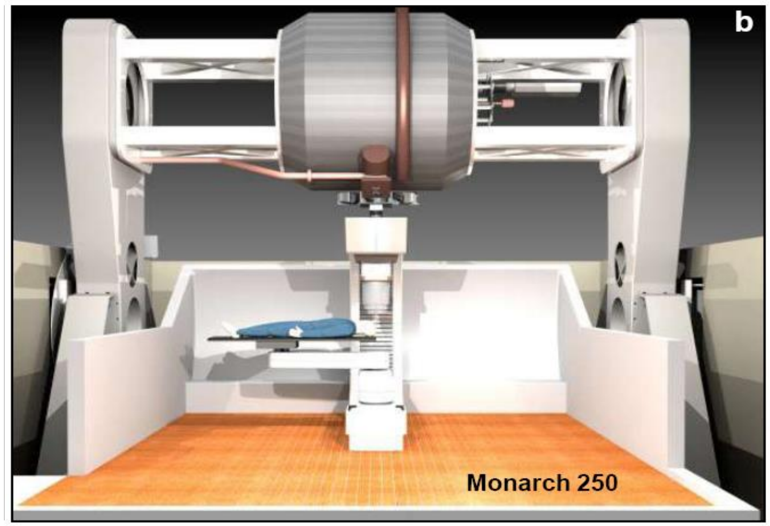
New challenges in hadrontherapy accelerators

Challenges for the new generation machines:

1. More compact (to fit in conventional hospitals): often cyclotron based, trend to single-room facilities.
2. Avoid complicated and expensive gantries.



The TULIP concept (TERA Foundation), compact linac rotating around the patient.

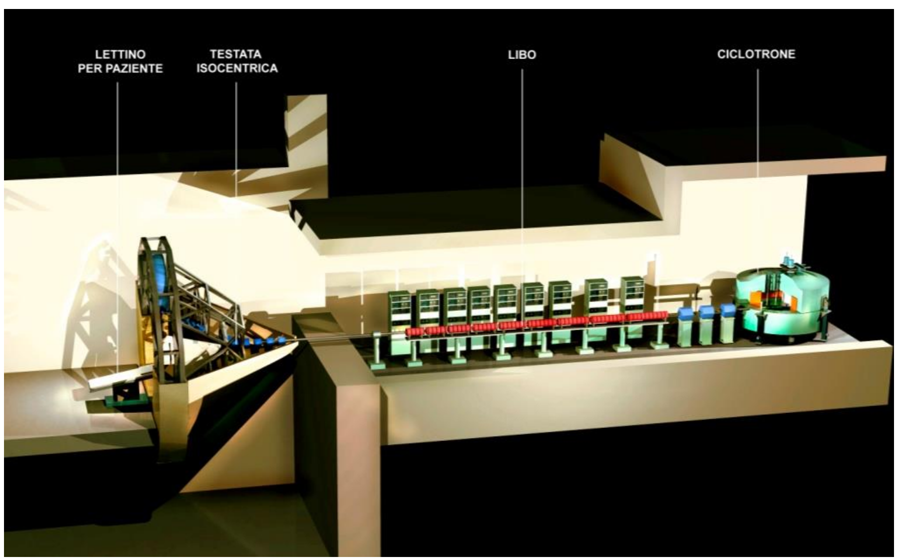


First single room facility: Still River synchrocyclotron rotating around the patient

Compact proton linacs for hadrontherapy

The LIBO (LInac BOoster) project (1993 – 2003)

Development of a 3 GHz Side-Coupled module as prototype for a compact linac to be used after a commercial cyclotron, to increase proton energy from about 70 MeV (existing cyclotrons) to values interesting for deep tumour treatment (200 MeV).



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The LIBO prototype

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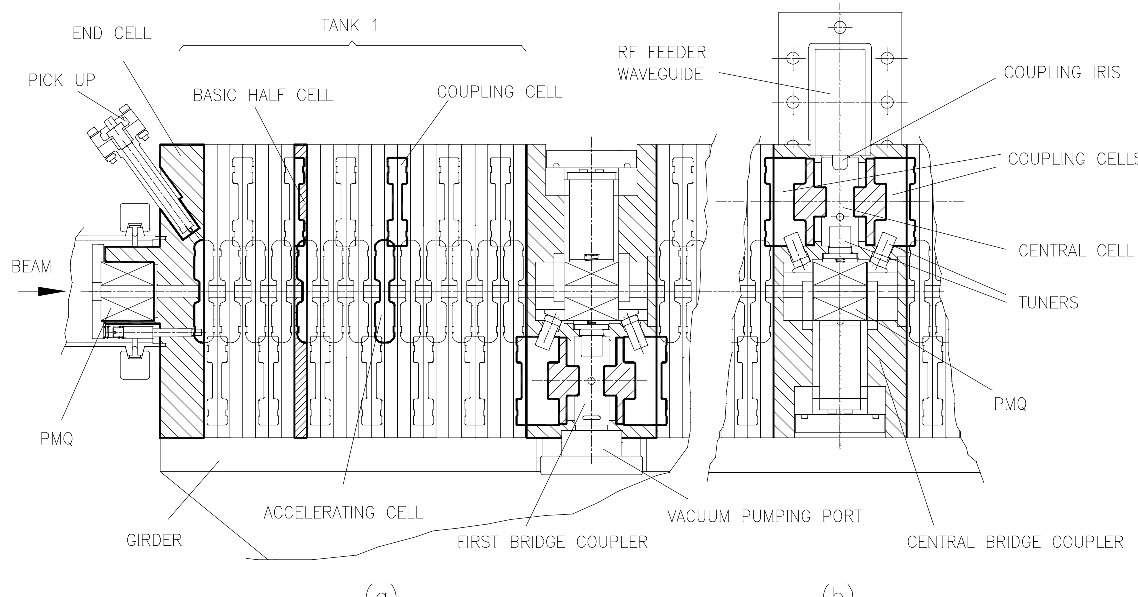
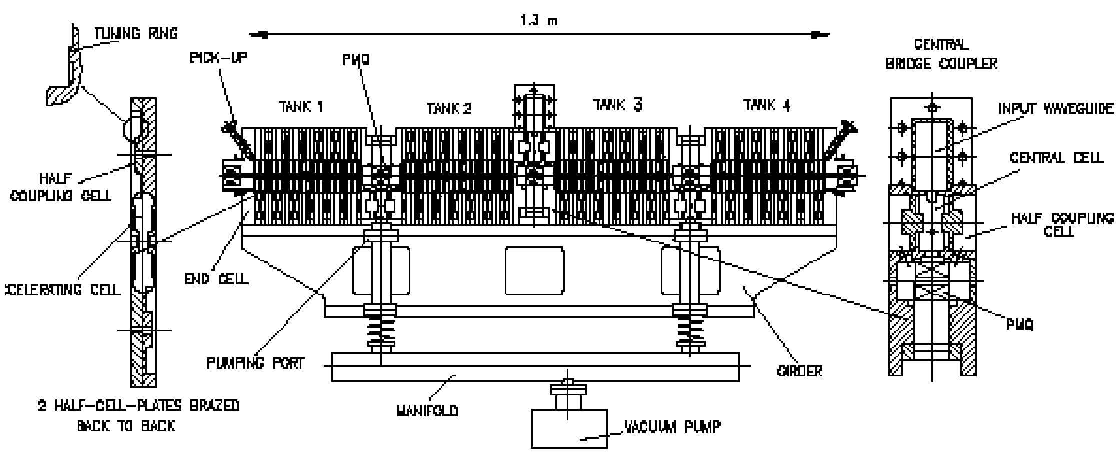
1st module, 62-74 MeV

3 GHz (e- linac standard)
4 Side-Coupled tanks of 13 accelerating cells each, connected by bridge couplers of 3 cells each: a module contains 109 coupled cells in 1.3 m !



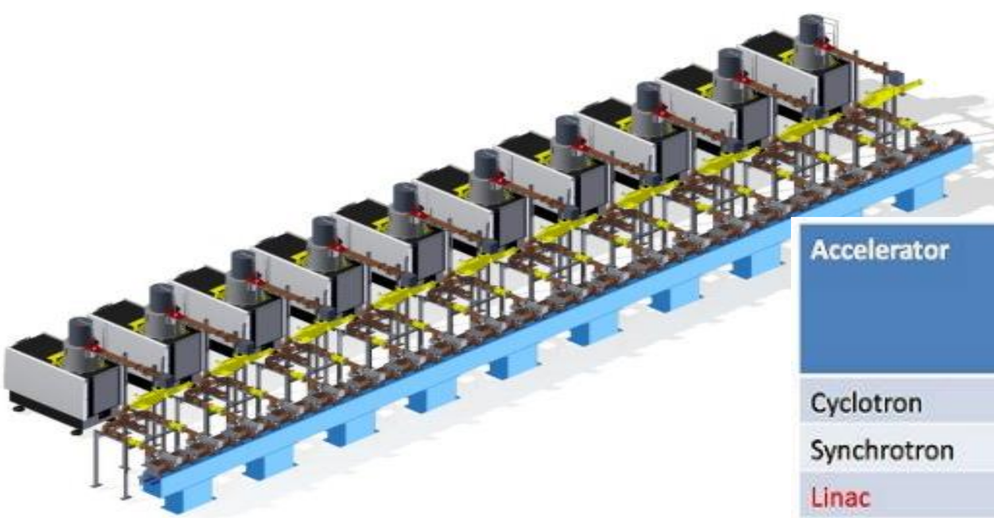


Compact proton linacs for hadrontherapy / 2

LIGHT (Linac for Image Guided Hadron Therapy) project developed by the ADAM company in collaboration with CERN (related to TERA)

Recently built and successfully tested a prototype unit (2 modules).
Modular design, compact, output energy variation
Conventional proton linac as injector

LIGHT Parameters	Value
Typical LIGHT output proton beam energy	230 MeV
Typical LIGHT input beam energy	30 MeV
Typical number of acceleration module assemblies	10
Electronic beam energy variation range up to maximum energy	70%
Time required to change beam energy	2-3 msecs
Pulse repetition rate	200 Hz
Proton Linac typical length	20 metres



Accelerator	Beam always present during treatments	Energy variation by electronic methods	Time needed for varying the energy
Cyclotron	YES	NO	80-100 ms (*)
Synchrotron	NO	YES	1-2 seconds
Linac	YES	YES	2-3 milliseconds (**)

(*) With movable absorbers
(**) The energy is changed by adjusting the RF power to the modules

RFQ for Proton therapy

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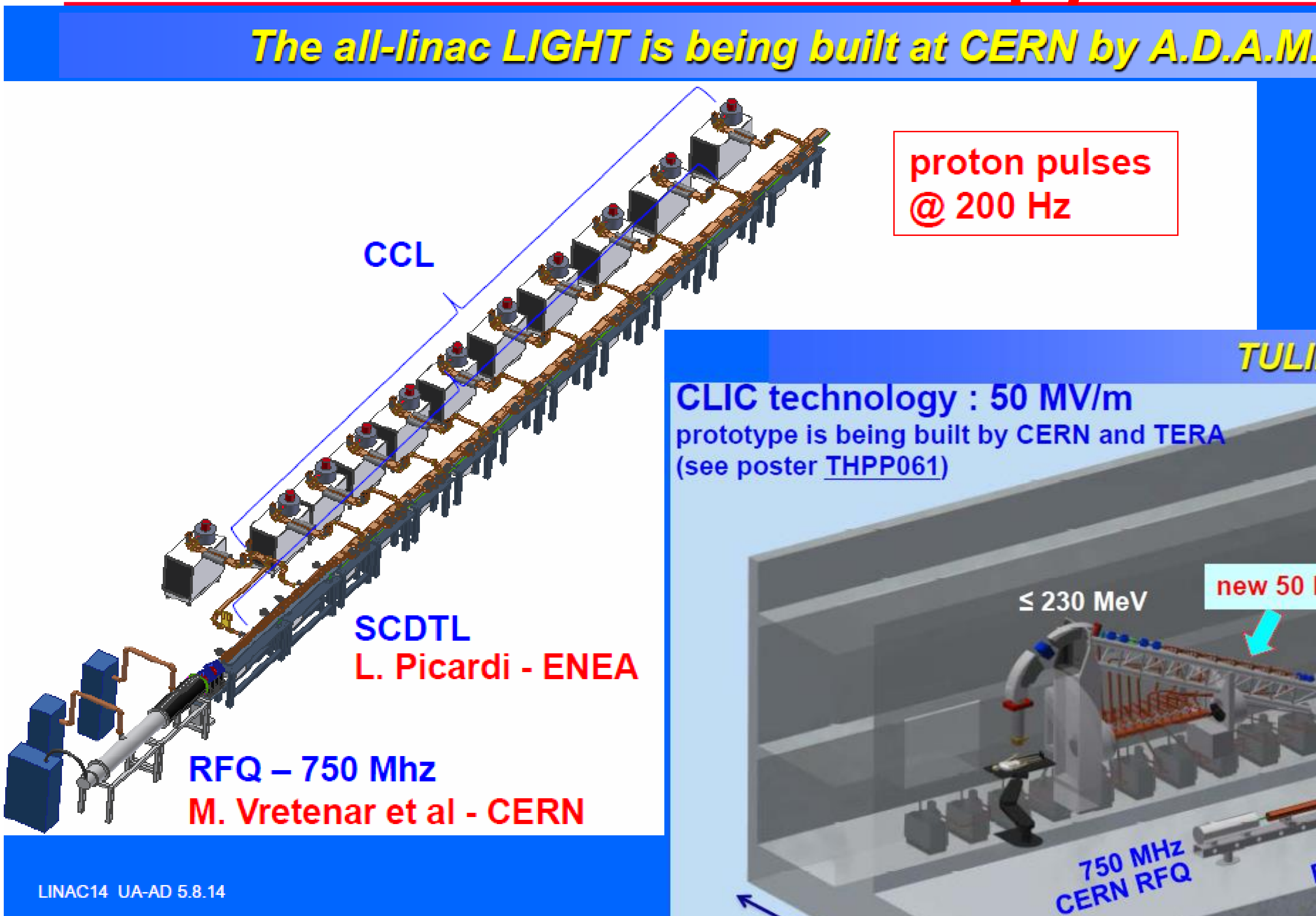
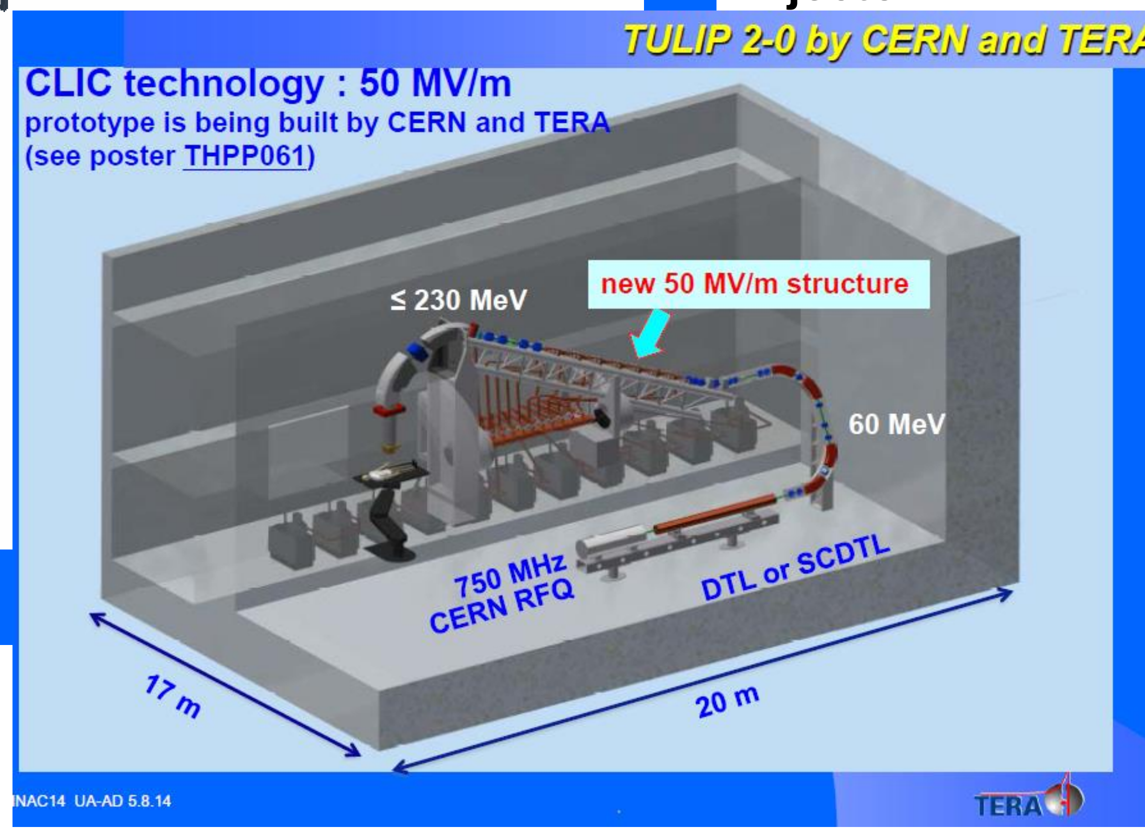


2 examples of proton therapy linacs using the HF-RFQ as injector



The 750 MHz RFQ project at CERN

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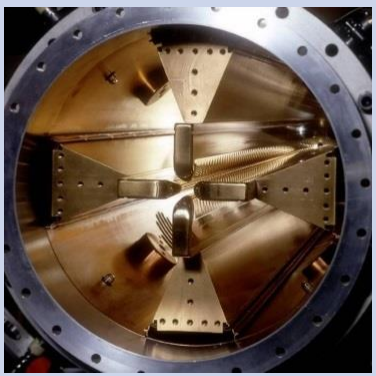
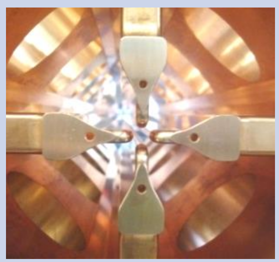
1990 RFQ2 200 MHz 0.5 MeV /m Weight : 1000 kg/m Ext. diameter : 45 cm	2007 LINAC4 RFQ 352 MHz 1MeV/m Weight : 400kg/m Ext. diameter : 29 cm	2014 HF RFQ 750MHz 2.5MeV/m Weight : 100 kg/m Ext. diameter : 13 cm
		

Higher Frequency (Constant aperture) → Shorter RFQ (Smaller cross-section) → Lower cost

Low current (< 2 mA) → Shorter RFQ (Controlled beam loss) → Higher gradient (for same vane voltage)

HIGHER FREQUENCY

Initial RFQs in the 200 MHz frequency range
Later, 400 MHz range (Linac4, 352 MHz).
New frequency range 700 – 800 MHz

New development at 750 MHz
-Smaller, less expensive construction
-More cells/unit length, shorter
But:
-Lower current capability
-Same range of RF power

Fabrication cost per meter about 50% at 750 MHz w.r.t. 350 MHz

Linacs vs. cyclotrons

- **Industrial and medical applications: standard low-energy accelerator is the cyclotron.**
- **Most of scientific applications: low-energy acceleration provided by linear accelerators.**

Two different (competing?) technologies coming from the same origin, the work of Ernest O. Lawrence team at Berkeley in the 30's – great success of the cyclotron, interest for linacs came only after WWII when high RF frequencies became available.

	Principle	Operation	Focusing	Extraction	Beam quality	RF power	Cost	Maintenance
CYCLOTRON	Cyclic (magnet based)	CW	Weak	Lossy	Average	**Low**	**Low**	Higher
LINAC	Linear (RF based)	Pulsed	**Strong**	**Clean**	**Good**	High	High?	**Lower**

12 MeV section (from left, DTL1, RFQ, source) of the CERN Linac4 under commissioning at CERN. Linac4 is 80 meters, 160 MeV, 80 MEUR (500 kEUR/MeV building and infrastructure included)

E. O. Lawrence

Technological Roadmap

Develop a modular high-frequency RFQ design covering 3 applications:

1. Injector for proton therapy linac
   - 5 MeV
   - Low current
   - Low duty cycle (<1%)
   - In construction

2. Isotope production in hospitals
   - 10 MeV
   - Low current
   - Medium duty cycle (<5%)
   - Design

3. Brachytherapy isotopes or Technetium production in dedicated centers
   - 20 MeV
   - Includes DTL linac
   - High current
   - High duty cycle (10%)
   - Preliminary design

Increasing complexity from one step to the next, will profit of experience from previous step

Proton therapy RFQ at 750 MHz (submultiple of 3 GHz), others in range 700-800 MHz

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Basic parameters

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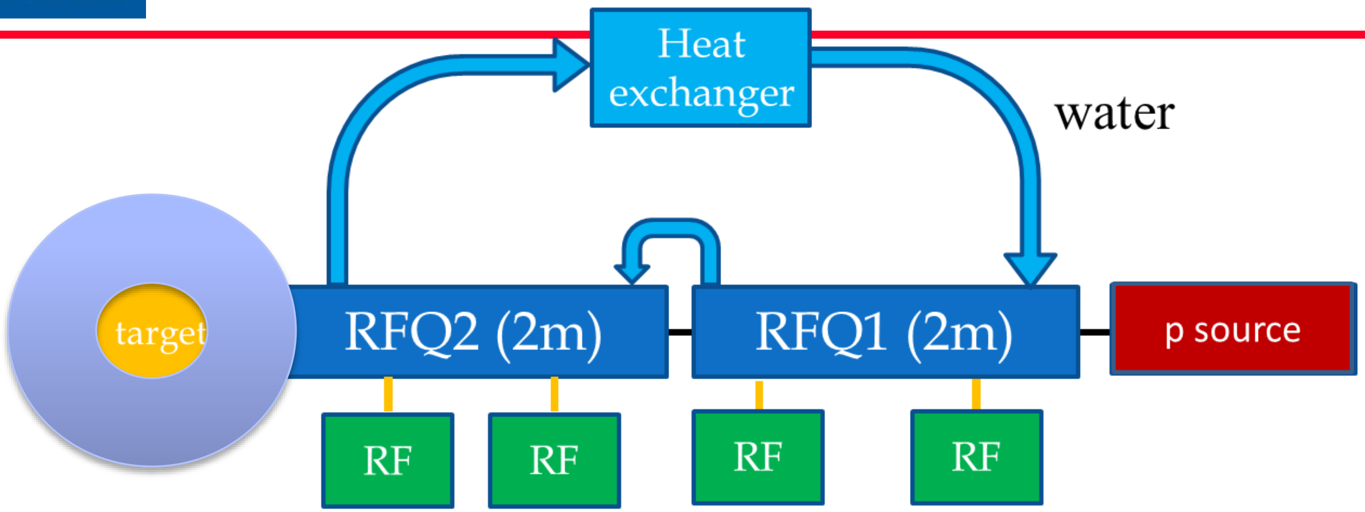
	Step 1	Step 2	Step 3	
Application:	Injector for Hadron Therapy Accelerator	PET Isotope Production	^{99m}Tc Production	Isotope Production for Brachytherapy
Particle:	p^+	p^+	p^+	α / d^+
Beam energy (MeV)	5	10	18	20
Accelerator length (m)	2	4	≈10	≈10
Average current (mA)	0.015	0.02	1	~0.1
Peak current (mA)	0.3	0.5	10	~1
RF Frequency (MHz)	750	750	704	704
Duty Cycle (%)	< 1	4	10	10
Peak RF Power (kW)	400	800	≈1500	≈1500

Note: higher current (~10 mA) can be obtained with a lower frequency RFQ (eg. 350 MHz)

The isotope RFQ system

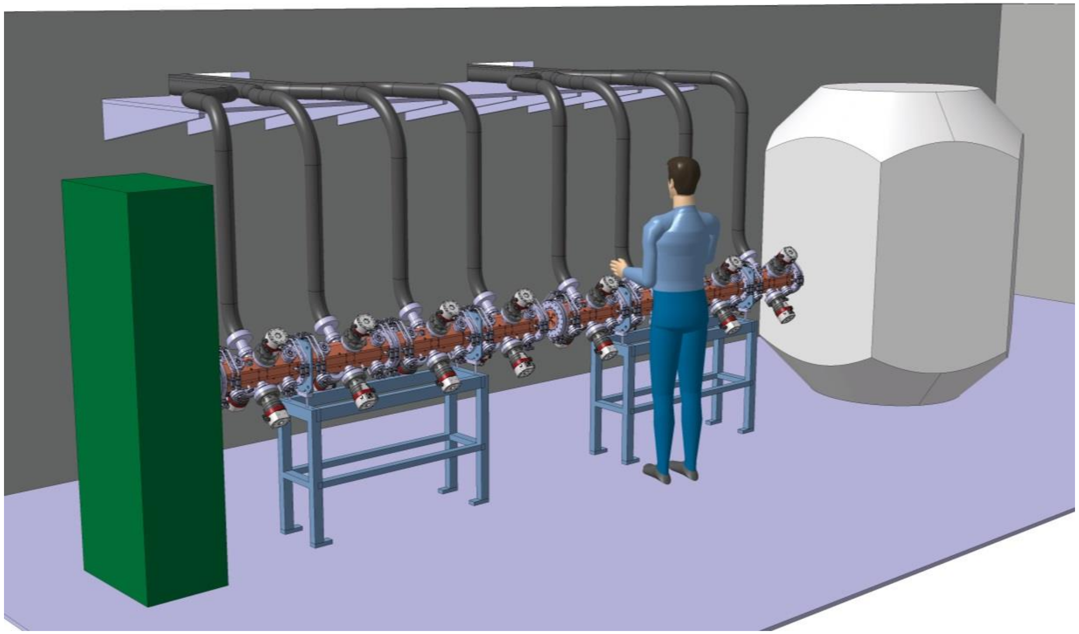


To be installed in hospitals (or movable on a lorry?)

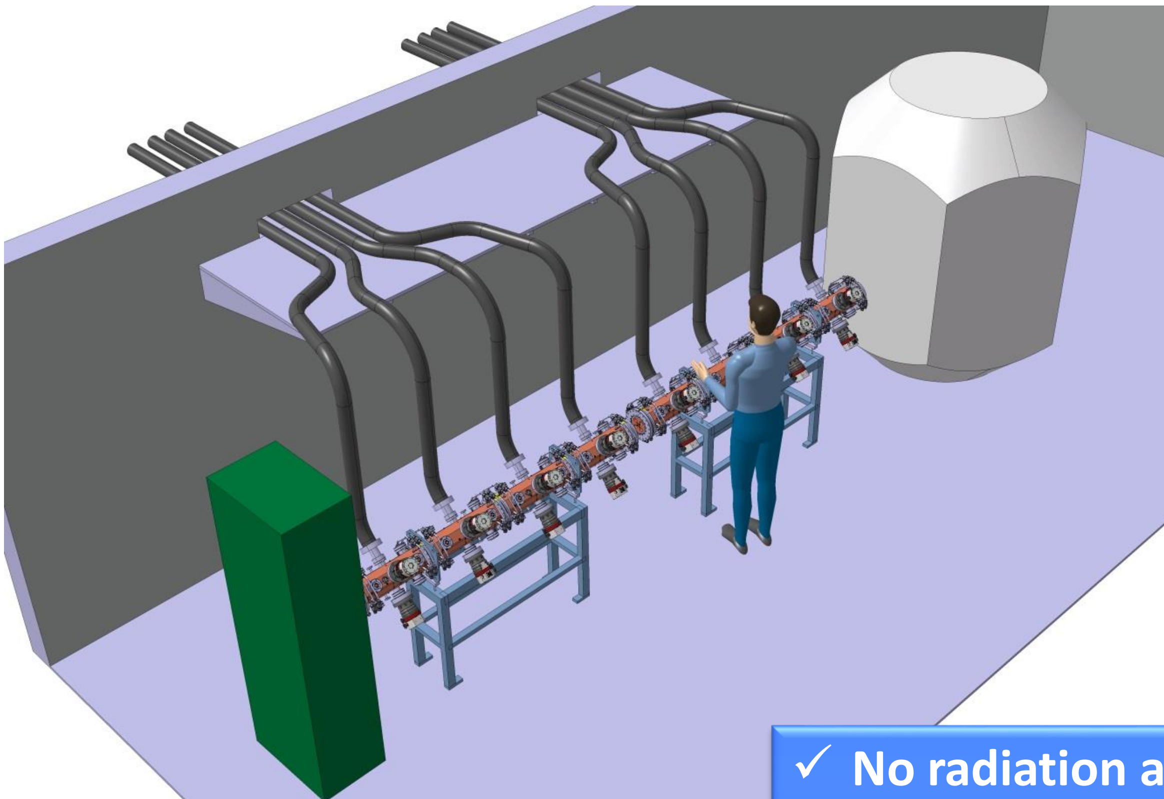
2 (or more) movable targets.

Target shielded by layers of iron and borated (6%) polyethylene, overall radius <0.9 m.

Maximum calculated dose at shielding 2 μSv/h



Parameters for isotopes



2 RFQs
Input energy = 40 KeV
Total Length = 4.0 m
Output Energy = 10 MeV
Frequency 750 MHz
Average current = 20 μA
Peak current = 500 μA
Duty cycle = 4 %
Peak RF power < 800 kW
Total weight (RFQ): 500 kg
Mains power < 65 kW
Cooling ~ 100 l/min

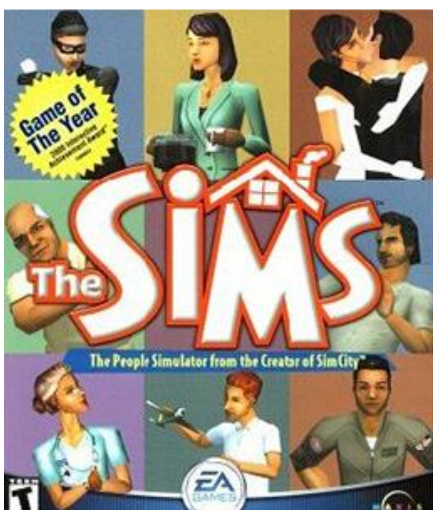
Production for PET scans of ^{18}F and ^{11}C

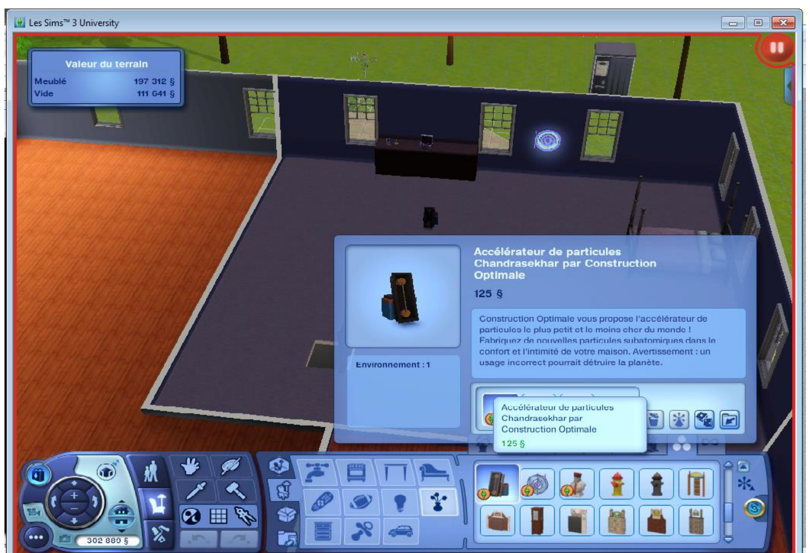
- ✓ No radiation around accelerator and target.
- ✓ Easy operation (one button machine).
- ✓ High reliability
- ✓ Minimum footprint (15 m2)

The miniature accelerator: a linac?

Next challenge: the miniature accelerator!

- Brings protons above Coulomb barrier
- Could fit in your kitchen (or in a standard industrial environment)
- Allow you to stay next to it while it works (low radiation!)
- Is cheap, reliable and maintenance-free





AVAILABLE IN THE VIRTUAL WORLD: In "The SIMS" (life simulation video game) you can already buy: *"the smallest and cheapest particle accelerator in the world. Produce new subatomic particles in the comfort and intimacy of your home. Notice: a wrong usage could destroy the planet."*