Accelerator Driven Transmutation

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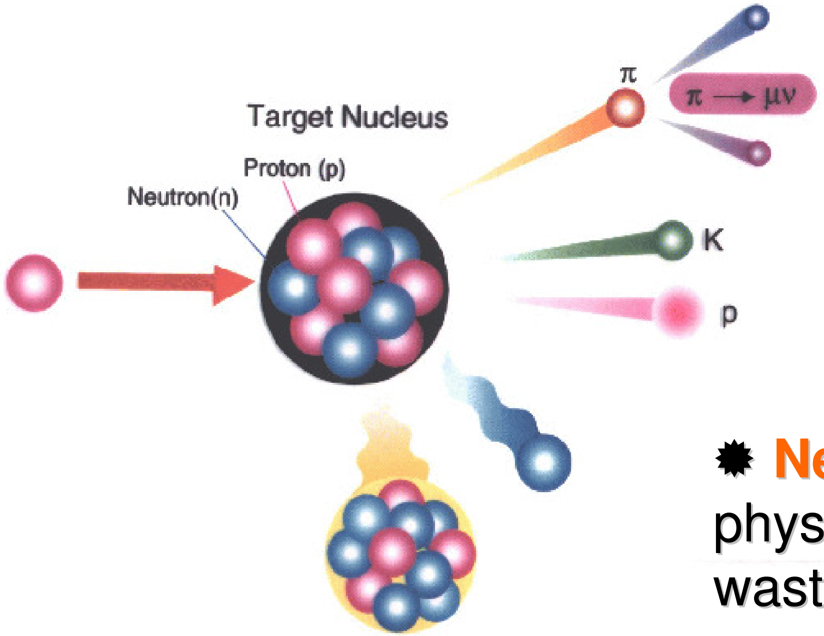
1. Introduction

2. The P&T strategy
3. The European ADS project: MYRRHA
4. ADS accelerator specificities
5. The MYRRHA accelerator R&D
6. Conclusion

High power proton accelerators

Production of **intense flux of secondary particles**
relevant for several domains of fundamental or applied science



✹ Muons, neutrinos... for **Particle physics**

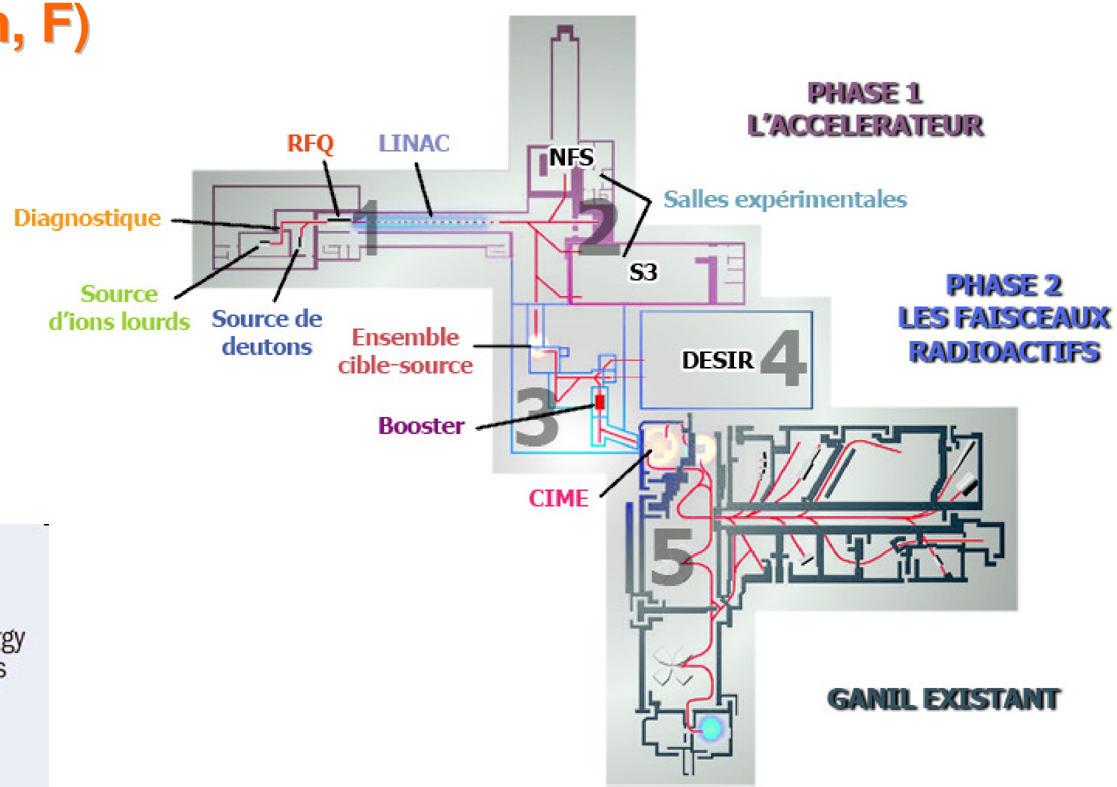
✹ **Neutrons** for condensed matter physics, material physics, irradiation, transmutation of long-lived nuclear wastes...

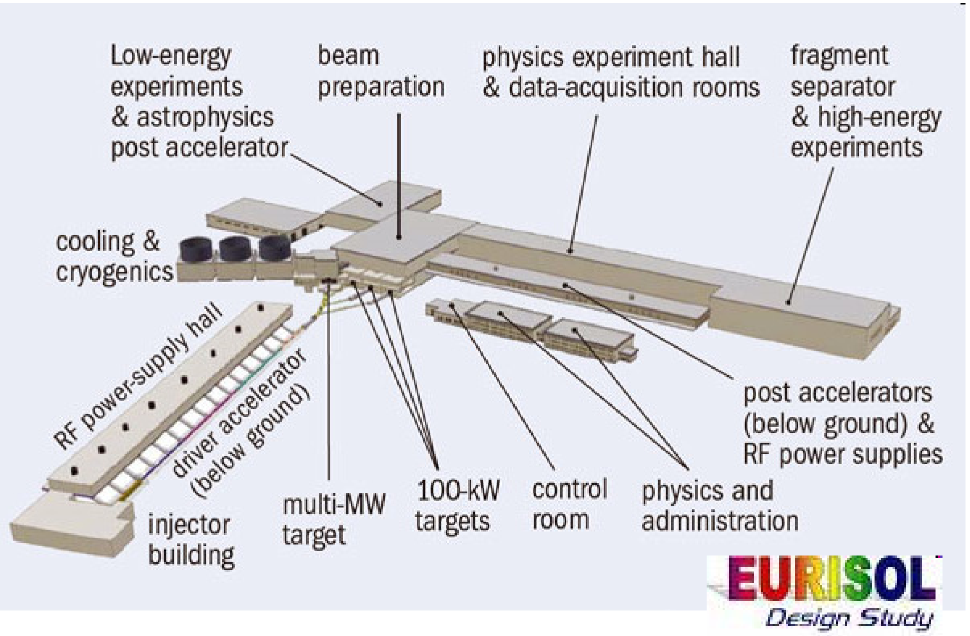
✹ Radioactive ions… for **Nuclear physics**

Example #1: SPIRAL-2 (GANIL) & EURISOL

✹ SPIRAL-2 project @ GANIL (Caen, F)

- Physics of exotic nuclei mainly, using the ISOL method
- Primary beams: protons, deuterons, heavy ions, up to 200 kW CW
- Phase 1 (driver linac) under construction





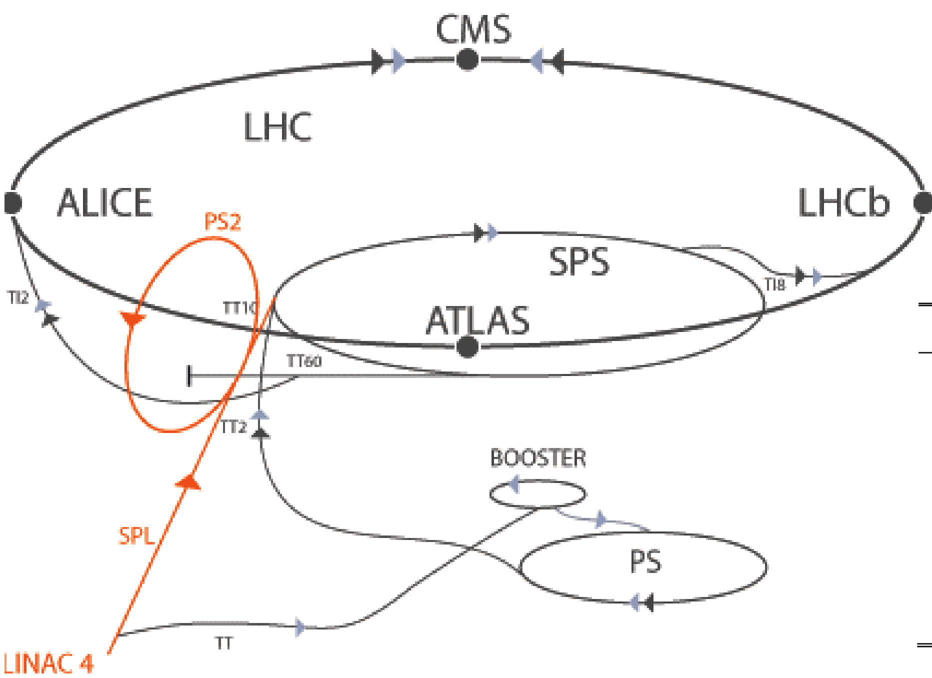
✹ EURISOL project

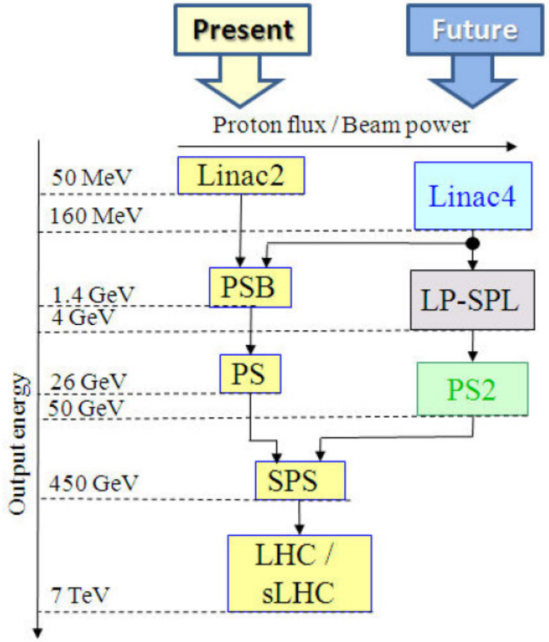
- New generation radioactive ion beam facility (ISOL method)
- Primary beams up to 5 MW

Example #2: SPL project (CERN)

SPL project @ CERN

- LHC luminosity upgrade
- Neutrino physics
  (π, μ decay, or ^{6}He, ^{18}Ne decay)
- Compatible with EURISOL
- LINAC 4 (160 MeV) under construction





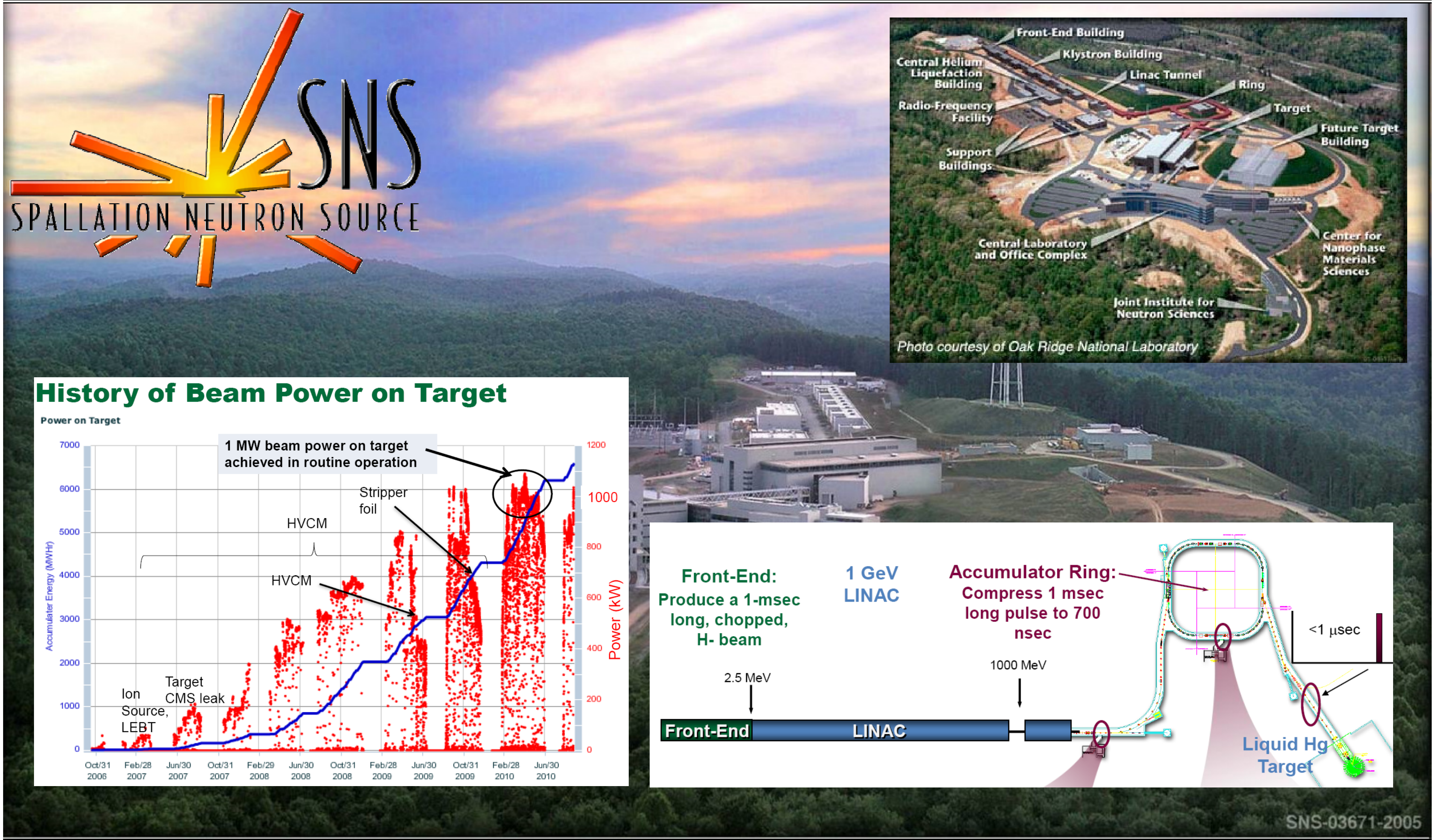
LP-SPL: Low Power-Superconducting Proton Linac (4 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
sLHC: "Super-luminosity" LHC (up to 10^{35} cm^{-2}s^{-1})

Table 2: Low Power and High Power SPL beam characteristics

	LP-SPL	HP-SPL Option 1	HP-SPL Option 2
Maximum kinetic energy [GeV]	4	4 or 5 [a]	4 or 5 [a]
Average beam current during pulse [mA]	20	20	40 [b]
Pulsing rate [Hz]	2	50	50
Pulse duration [ms]	0.9	0.9	1.2 [b]
Beam power [MW]	0.14	2.25 @ 2.5 GeV **or** 4.5 MW at 5 GeV	5 @ 2.5 GeV **and** 4 MW at 5 GeV

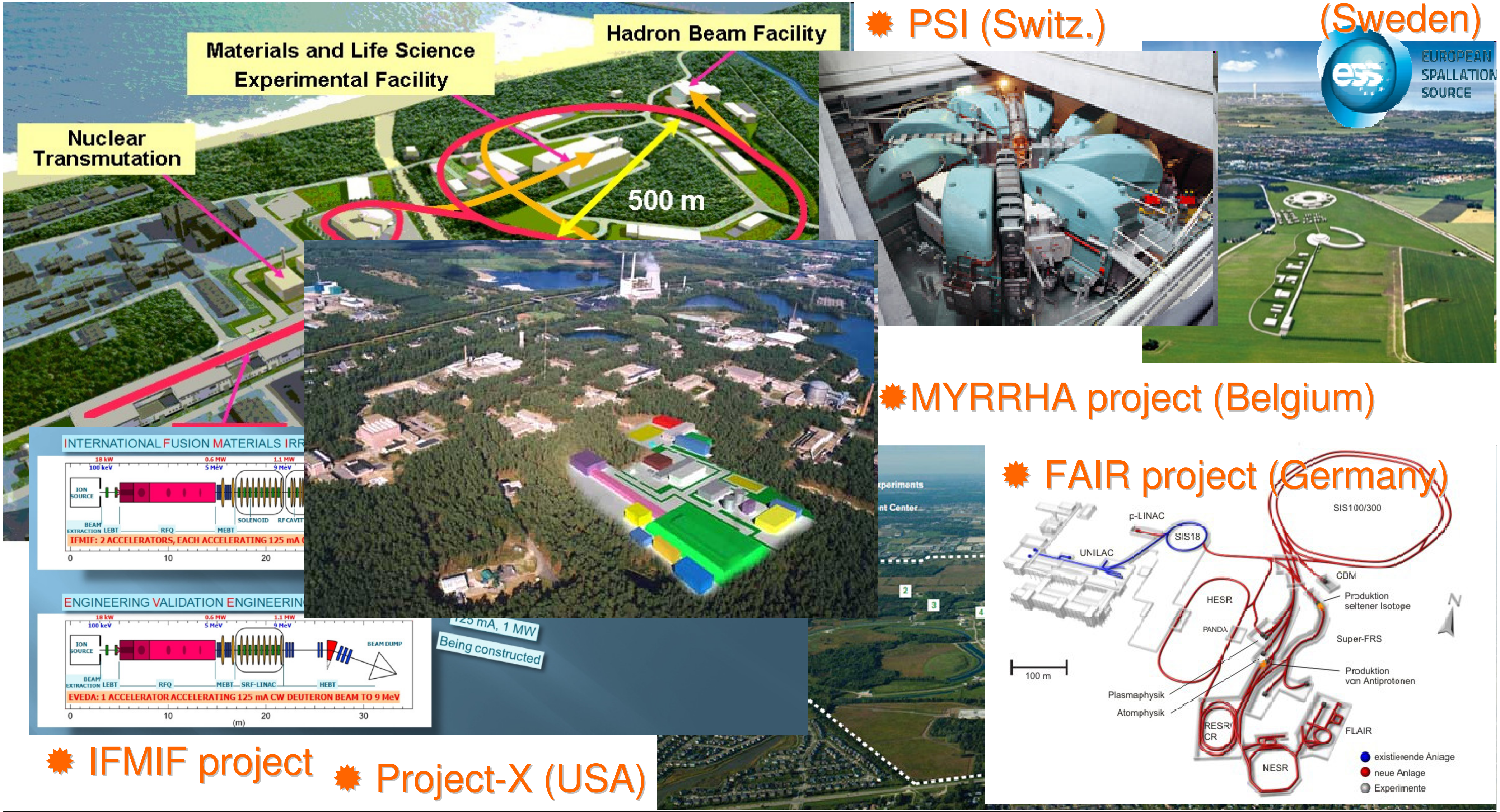
[a] Required for a neutrino factory.
[b] Required for 2 simultaneous users of high beam power or for 5 MW at 2.5 GeV

Example #3: SNS (Oak Ridge, USA)



Other machines & projects

- J-PARC facility (Japon)
- ESS project (Sweden)
- PSI (Switz.)
- MYRRHA project (Belgium)
- FAIR project (Germany)
- IFMIF project
- Project-X (USA)



Main associated challenges

These high power machines require an **excellent beam transmission** to be allowed to operate: beam loss level must be $< 10^{-6}$ per meter typically

Physics of intense hadron beams

- Management of space charge effects
- Understanding of beam halo generation during transport

R&D on new technologies

- Accelerating cavities (RFQ, superconducting cavities)
- Diagnostics for intense hadron beams
- New generation targets (MegaWatt)
- High power Radio-Frequency elements

Increased demand for flexibility and reliability

- Higher & higher beam availability is required
- High diversity of primary beam in a single machine (nuclear physics application)
- Beam interruptions forbidden (ADS application)

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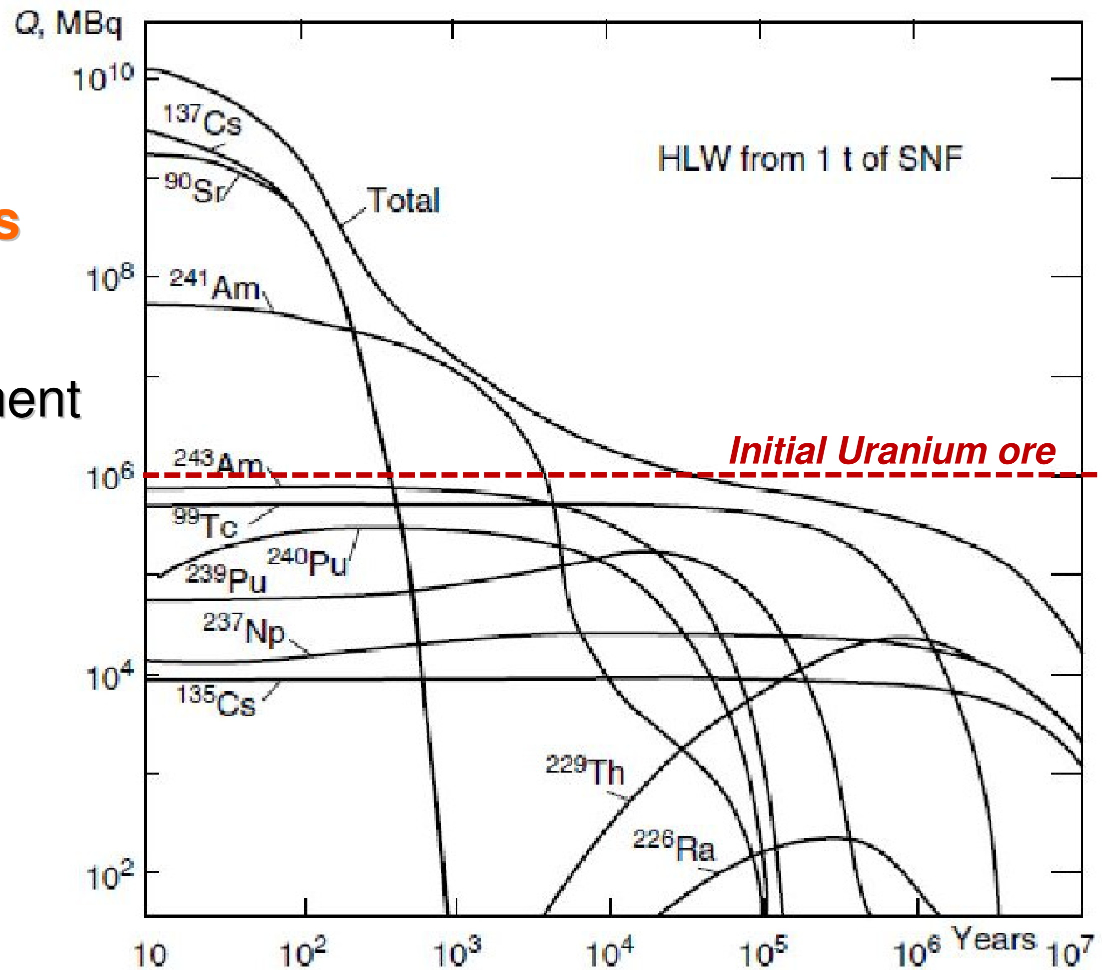
Nuclear wastes

➢ About 2500 tons of Spent Nuclear Fuel are produced every year by the 145 reactors of EU

➢ High Level Wastes represent 0.2% in volume & 95% in radiotoxicity and are long-term dominated by **Minor Actinides** (MA, especially ^{241}Am)

➢ Reference solution for HLW management = long-term **geological disposals**

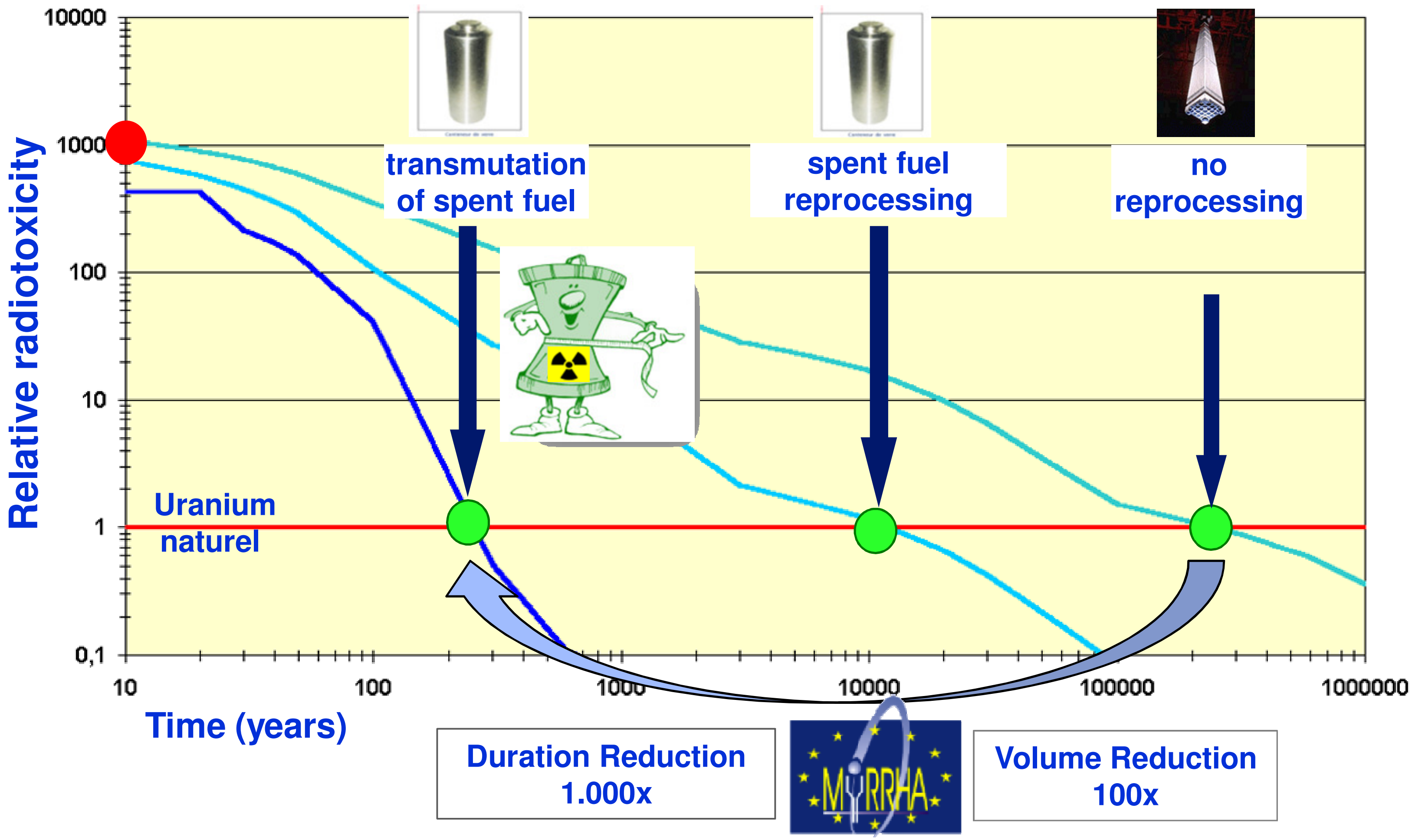
The Yucca Mountain Nuclear Waste Repository (USA) project de-funded in 2011



Activity of High Level Waste remaining after processing of 1 ton of Spent Nuclear Fuel in dependence of time

Motivation for Partitioning & Transmutation

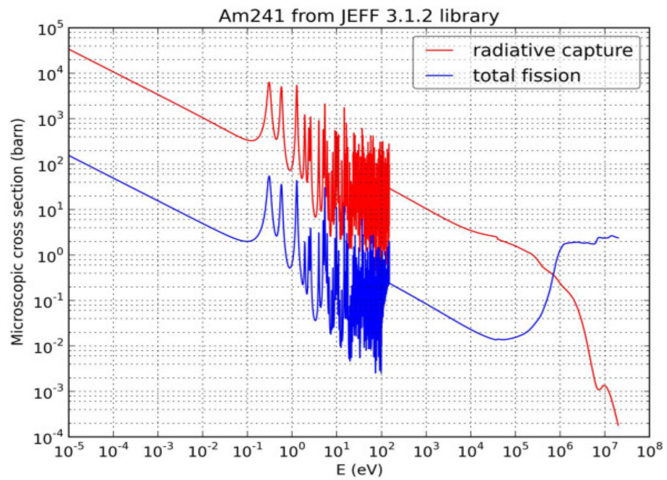
➢ **Partitioning & Transmutation (P&T) strategy:** reduce radiotoxicity, volume and heat loads of long-lived nuclear wastes (MA) before geological storage



H. Aït Abderrahim (SCK•CEN)

Present options for MA transmutation

Transmutation of MA into fission products is efficient only if:



- Fission to capture cross section ratio is high enough
- Enough neutrons are available to feed the transmutation process

=> **Need for a fast neutron spectrum**

In which type of fast reactor could we transmute ?

- In the next generation **GEN-IV nuclear power plants** (critical Fast Reactors)
  - ✓ homogeneous mode with low AM content in fuel (< 3%) for safety reasons
  - ✓ heterogeneous mode (MA blankets)
- In a few **dedicated MA burners** (subcritical Accelerator Driven Systems), highly loaded with MA

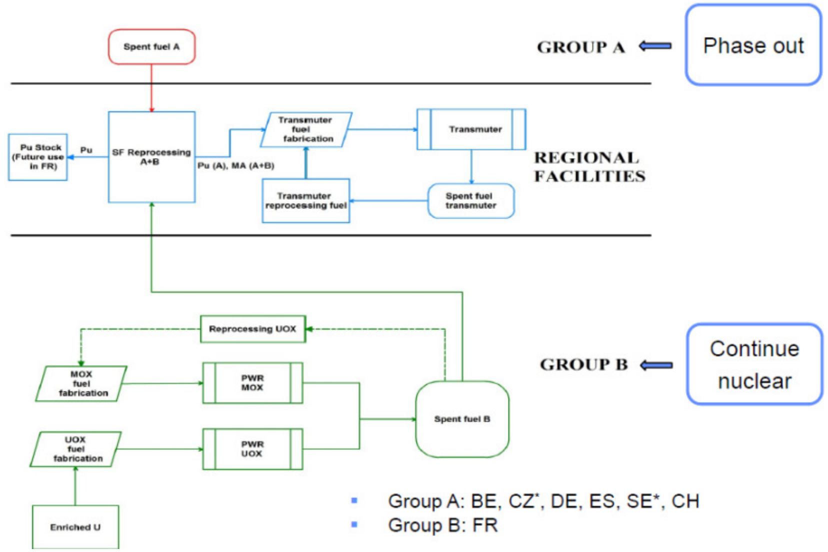
=> sensitive compromise btwn **safety / economics / proliferation / politics…**

ADS (Accelerator Driven System)

ADS sub-critical systems = present reference solution for <u>dedicated</u> “transmuter” facilities

➢ Suited for various strategies on nuclear energy

➢ One “small” 400 MWth industrial ADS could burn about 100kg of MA / year (→ 10 to 20 units for EU)



G. Van den Eynde (SCK•CEN)

ADS reactor specificities

➢ Neutron multiplication factor $k_{eff}<1$ (typically between 0.93 & 0.97)

➢ Driven by external neutron source (proton beam + spallation target)

$$P_{fi} = \eta_{sp} \cdot \frac{\varphi^* \cdot k}{\nu(1-k)} \cdot \frac{i}{C} \cdot E_f$$

where,
η_{sp} = spallation neutron yield (≈ 30 for Pb target)
k = neutron multiplication factor
φ^* = source importance (≈ 1.5)
ν = neutrons emitted per fission (≈ 2.5)
E_f = energy generated per fission ($\approx 3.1x10^{-10}$ W)
i = accelerator current
C = charge of a proton ($= 1.6x10^{-19}$ C)

➢ No control rods, no safety rods

➢ Some very fast neutrons (> 20 MeV) in the core

Background in France & Europe since 1990

➢ (FR) **Law « Bataille » n° 91-1381, 30 december 1991**
=> French roadmap for research on radioactive waste management

➢ (EU) ETWG report on ADS, 2001

➢ (EU-FP5) **PDS-XADS** project (2001-2004)

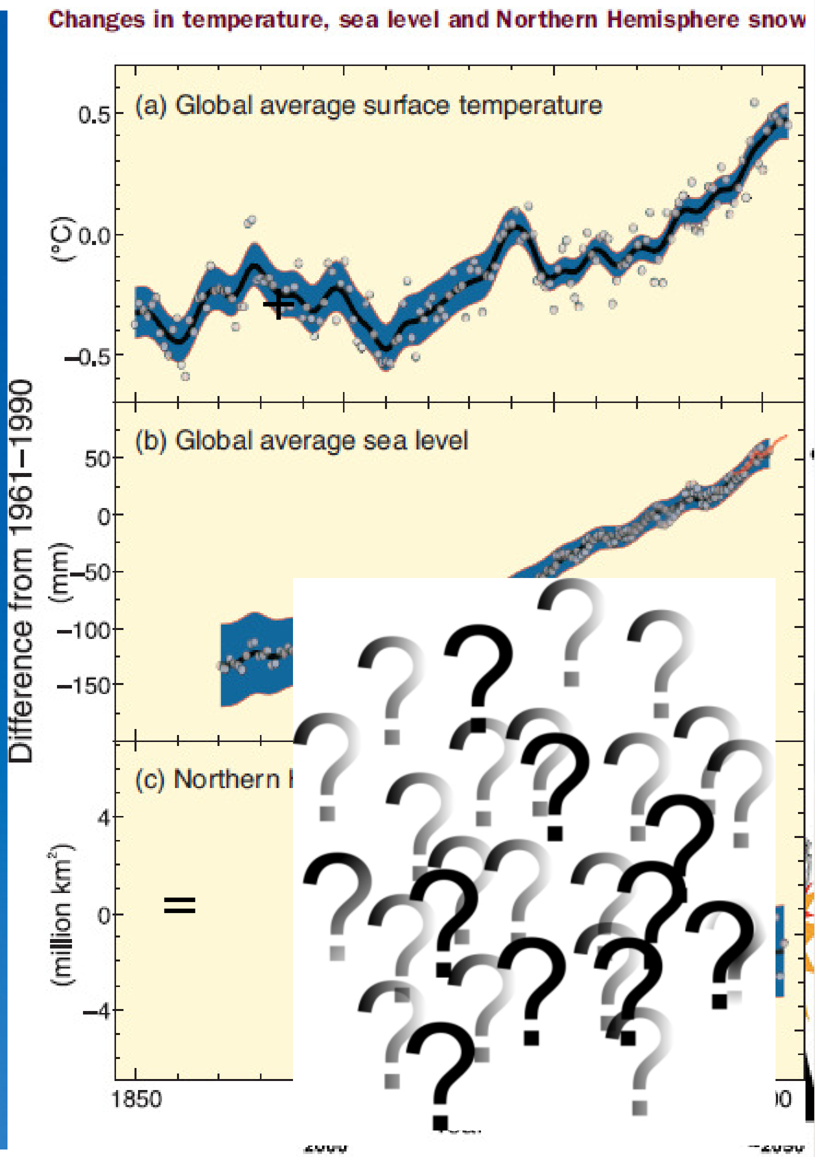
➢ (EU-FP6) **EUROTRANS** programme (2005-2010)

➢ (EU-FP7) On-going programmes (2011-2015)

➢ (FR) **Law n°2006-739, 28 june 2006**
=> Following-up the law « Bataille », with focus on sustainability

Article 3 (...) 1. La séparation et la transmutation des éléments radioactifs à vie longue. **Les études et recherches correspondantes sont conduites en relation avec celles menées sur les nouvelles générations de réacteurs nucléaires** mentionnés à l'article 5 de la loi n° 2005-781 du 13 juillet 2005 de programme fixant les orientations de la politique énergétique ainsi que sur les réacteurs pilotés par accélérateur dédiés à la transmutation des déchets, **afin de disposer, en 2012, d'une évaluation** des perspectives industrielles de ces filières et de mettre en exploitation un **prototype d'installation avant le 31 décembre 2020** ; (...)

A complex issue in even more complex hazards…



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The MYRRHA project

MYRRHA Project

Multi-purpose hYbrid Research Reactor for High-tech Applications At Mol (Belgium)

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

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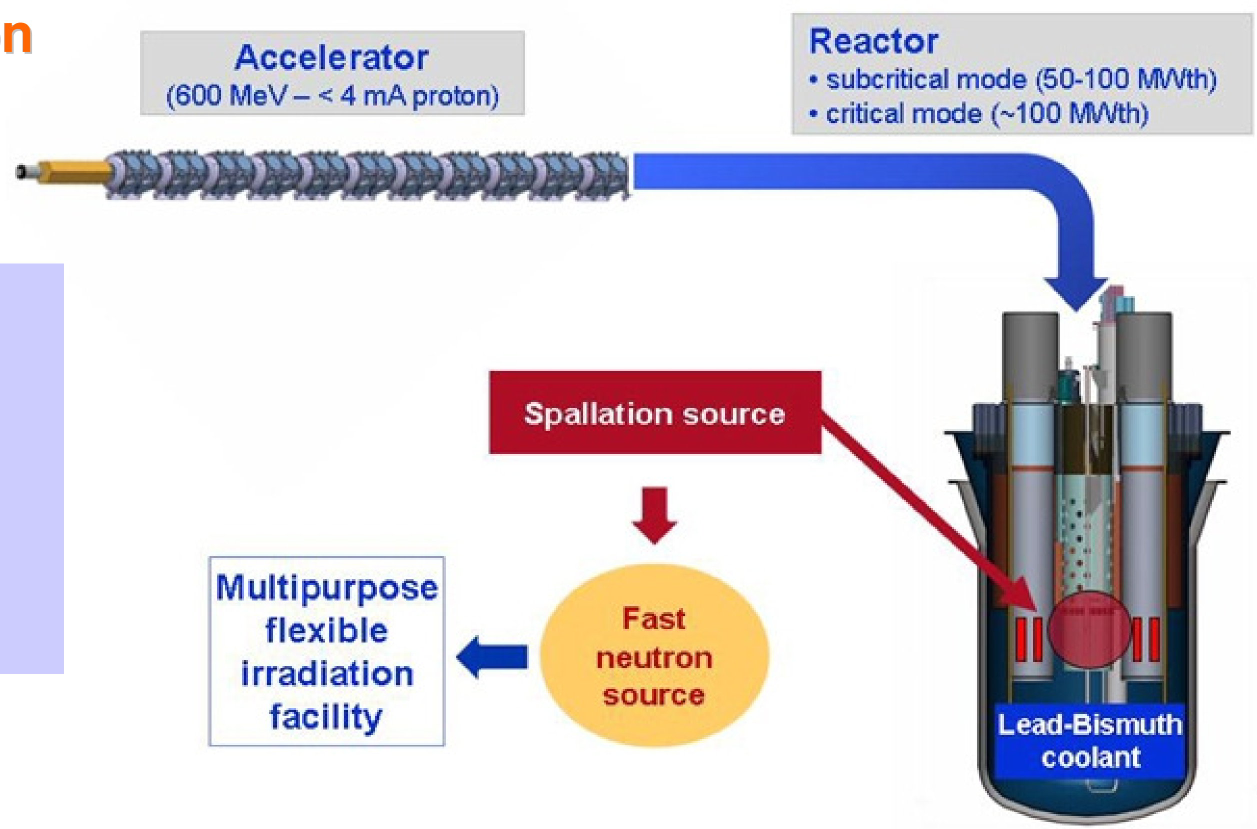
MYRRHA as an ADS demonstrator

Demonstrate the physics and technology of an Accelerator Driven System (ADS) for transmuting long-lived radioactive waste

- Demonstrate the **ADS concept**
(coupling accelerator + spallation source + power reactor)

- Demonstrate the **transmutation**
(experimental assemblies)



Main features of the ADS demo

50-100 MWth power

Highly-enriched MOX fuel

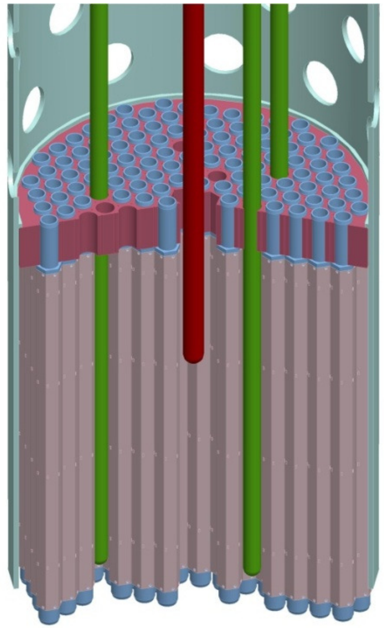
Pb-Bi Eutectic coolant & target

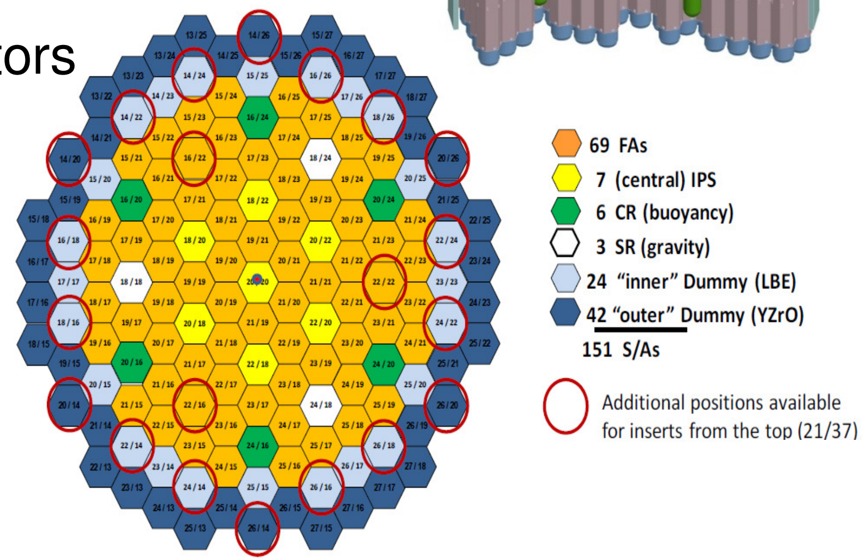
k_{eff} around 0.95 in subcritical mode

600 MeV, 2.5 - 4 mA proton beam

MYRRHA reactor present layout

- Vessel
- Cover
- “Core barrel”
- Core support plate
- Core plug
- Above core structure
- Heat exchangers
- Pumps
- Diaphragm
- Core
- Fuel manipulators





MYRRHA as a fast spectrum irradiation facility

- All **European irradiation research reactors** are about to close within 20 years
- The **RJH** (Réacteur Jules Horowitz) project, is presently the only planned MTR (Material Tests Reactor), and provides mainly a thermal spectrum
- MYRRHA is the **natural fast spectrum complementary facility**

Réacteurs de recherche européens

Pays	*Réacteurs de recherche*	*Age en 2015 (ans)*
Belgique	*BR2 à Mol*	*52*
Hollande	*HRF à Petten*	*54*
Norvège	*HRP à Halden*	*55*
France	*Osiris à Saclay*	*49*
Suède	*R2 à Studsvik*	*Mis à l'arrêt en 2005*
République tchèque	*LVR15 à Řež*	*58*

Main applications of the MYRRHA irradiation facility

Test & qualification of innovative fuels and materials for the future Gen. IV fast reactor concepts (and for fusion energy)

Production of radio-isotopes for nuclear medicine (^{99}Mo especially)

Production of neutron irradiated silicon to enable technologies for renewable energies (windmills, solar panels, electric cars)

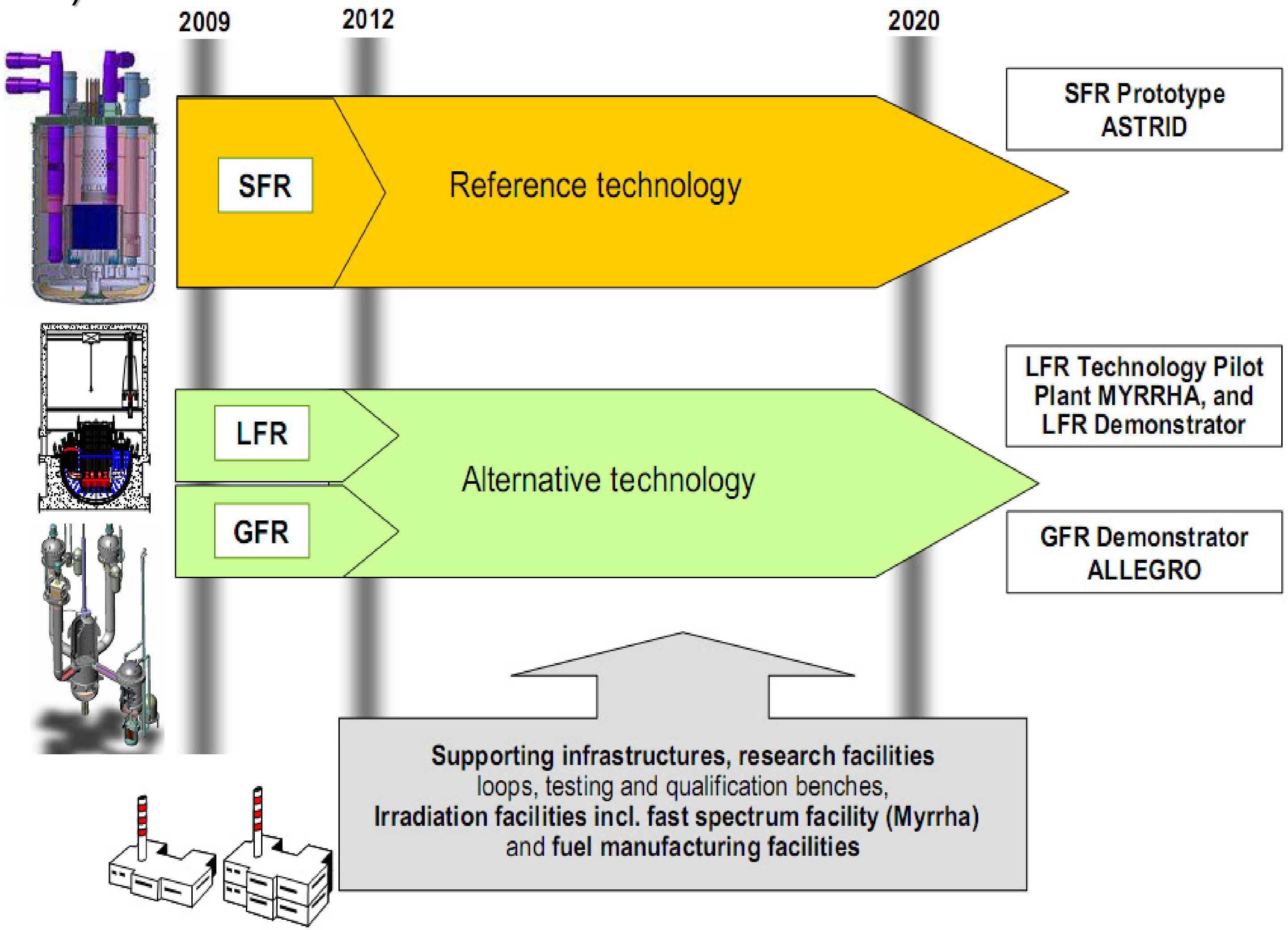
Fundamental science in general (also using the proton linac by itself)

MYRRHA as a Gen.IV demonstration reactor

Serve as a technology Pilot Plant for **liquid-metal based reactor concepts** (LFR "Lead Fast Reactors")

European commission scope for the development of Gen.IV advanced reactor systems demos

(ESNII roadmap)



SNETP
SUSTAINABLE NUCLEAR ENERGY TECHNOLOGY PLATFORM

MYRRHA in brief

MYRRHA is considered as **a strategic stone**

- For **SCK●CEN**, as a replacement for the BR2 reactor (shut-down in 2026)
- For the European picture of **Material Testing Reactors**, as a complement to the RJH
- For the future of **sustainable nuclear energy**, as an ADS demonstrator & a strong support to the development of Gen. IV reactors

SNETP
Sustainable Nuclear Energy Technology Platform

MYRRHA official key dates

- **1998**: first studies
- **2002**: pre-design "**Myrrha Draft 1**" *(cyclotron 350 MeV)*
- **2002-2004:** studied as one of the 3 reactor designs within the **PDS-XADS FP5 project** *(cyclotron turns into linac, fault-tolerance concept is introduced)*
- **2005:** updated design "**Myrrha Draft 2**" *(350 MeV linac)*
- **2005-2010:** studied as the XT-ADS demo within the **IP-EUROTRANS FP6 project** *(600 MeV linac conceptual design, R&D activities w/ focus on reliability)*
- **2010:** MYRRHA is on **the ESFRI list**, and is **officially supported by the Belgium government** at a 40% level (384M€, w/ 60M€ already engaged)
- **2010-2015:** engineering design, licensing process, set-up of the international consortium, w/ support from the **CDT, FREYA & MAX FP7 projects**
- **2016-2019:** construction phase
- **2020-2023:** commissioning and progressive start-up
- **2024**: full exploitation

MYRRHA within EURATOM FP7: 2010-2014

CDT

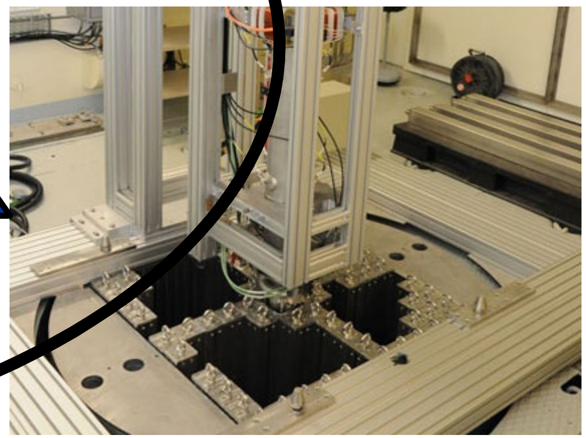
Reactor design

SCK•CEN

FREYA

GUINEVERE experiment

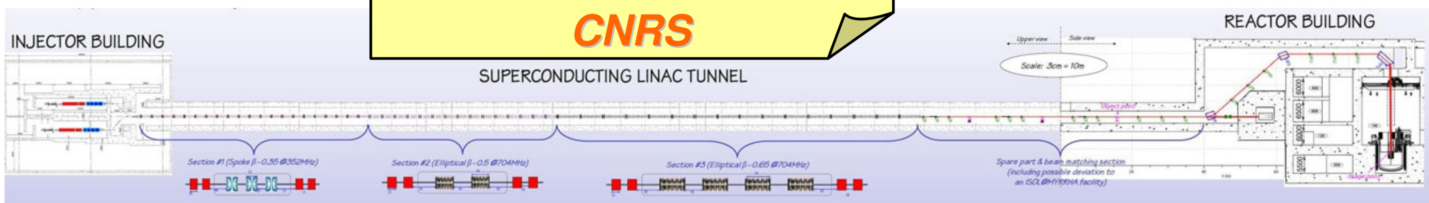
SCK•CEN



MAX

Accelerator design

CNRS



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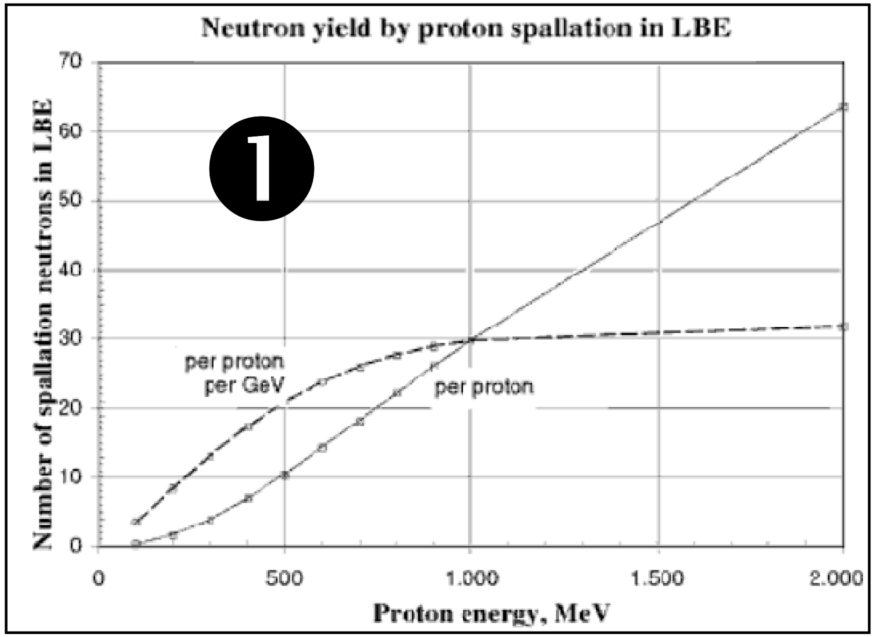
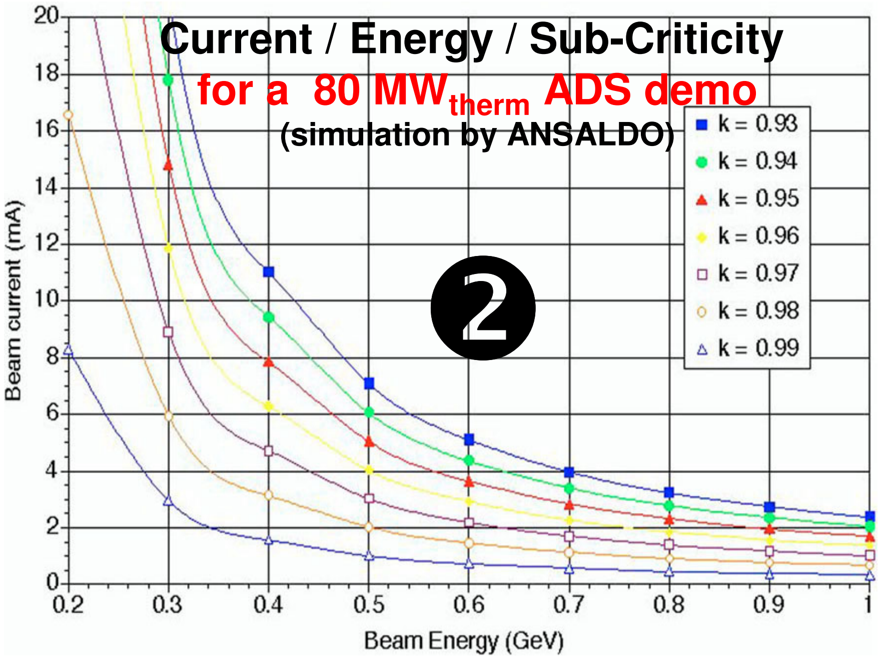
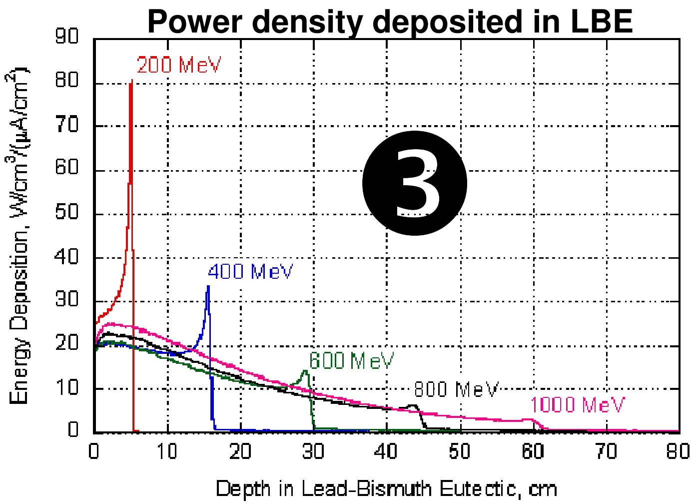
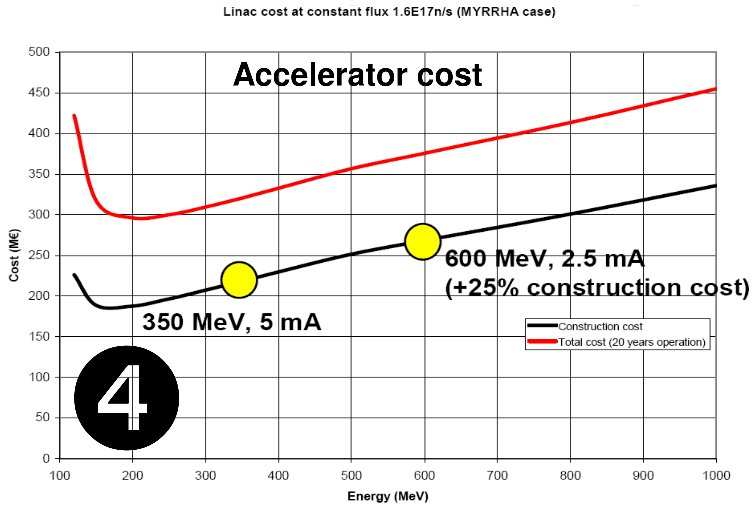
ADS proton beam requirements









ADS proton beam requirements

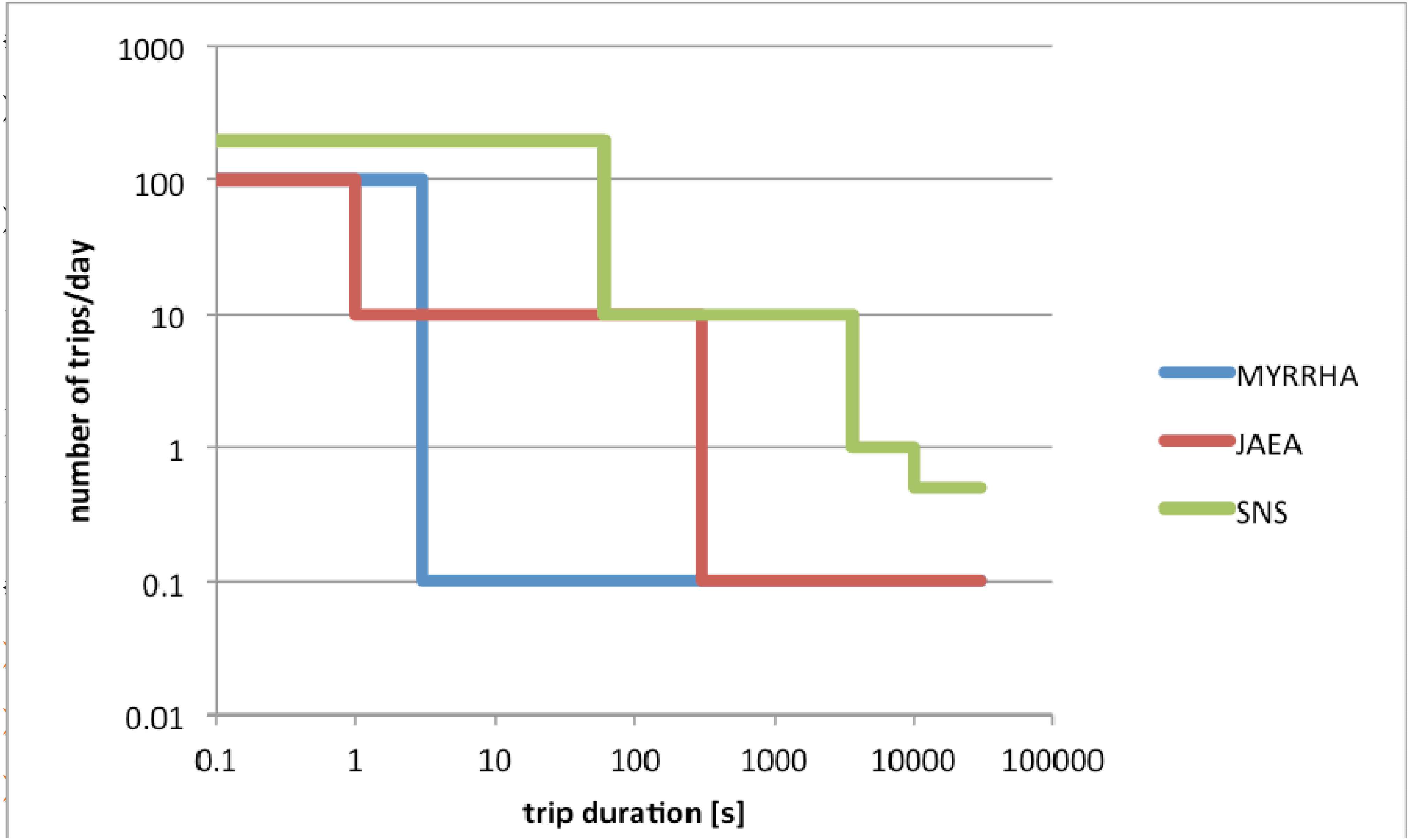
Proton beam general initial specifications within EUROTRANS

	Transmuter demonstrator (XT-ADS / MYRRHA project)	Industrial transmuter (EFIT)
Proton beam current	2.5 mA (& up to 4 mA for burn-up compensation)	~ 20 mA
Proton energy	600 MeV	800 MeV
Allowed beam trips nb (>3 s)	~ < 10 per 3-month operation cycle	~ < 3 per year
Beam entry into the reactor	Vertically from above	
Beam stability on target	Energy: ±1% - Current: ±2% - Position & size: ±10%	
Beam time structure	CW (w/ low frequency 200μs beam "holes" for sub-criticality monitoring)	

Extreme reliability level

Multi MW class CW beams

The reliability requirement



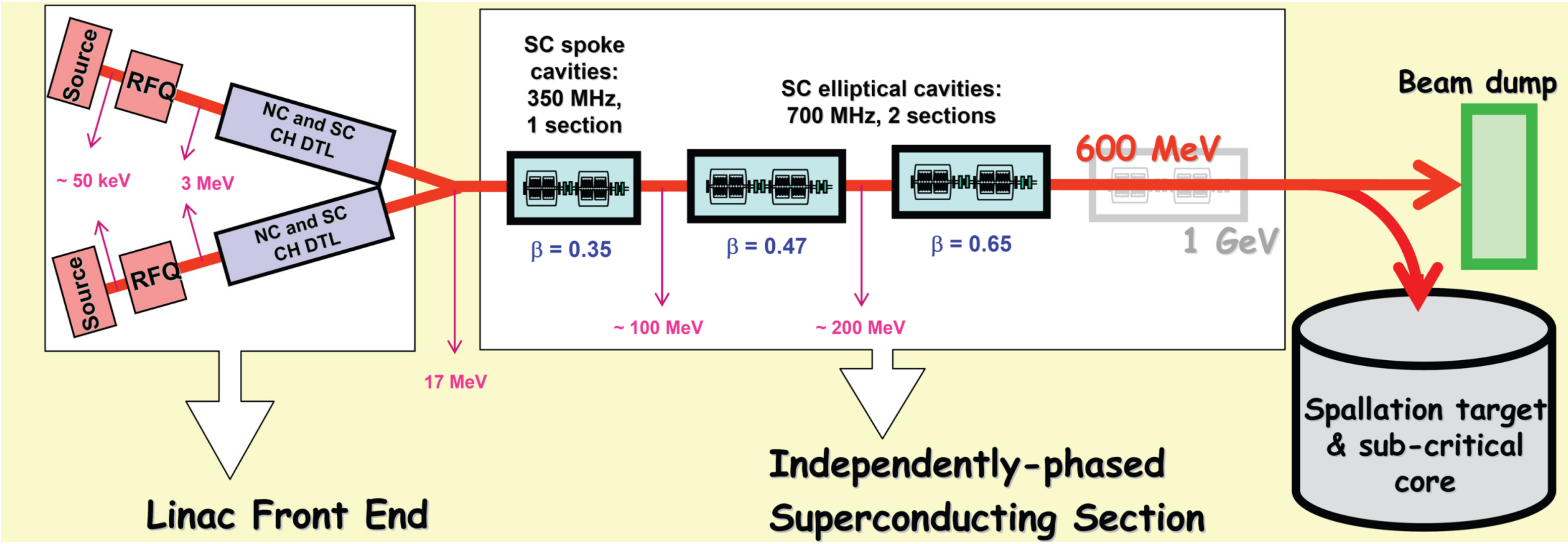
Generic scheme of the European ADS accelerator

Redundant injector

- Fault-tolerance is non applicable (β<0.15)
- Minimized number of elements
- Spare stand-by injector with fast switching capabilities

Modular SC main linac

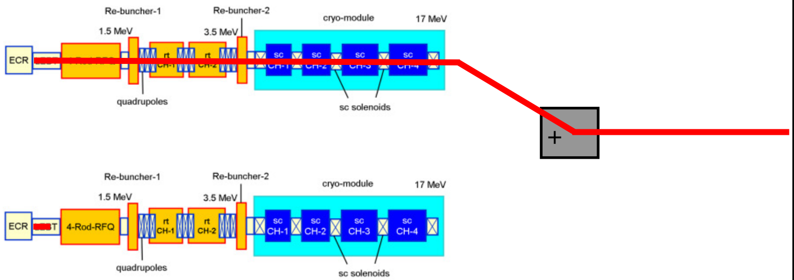
- Upgradeable concept (demo, transmuter)
- Independently-controlled elements
- The function of a missing element can be replaced by retuning adjacent elements ("FAULT-TOLERANCE")



Strategy for a fault case in the injector

❶ Initial configuration

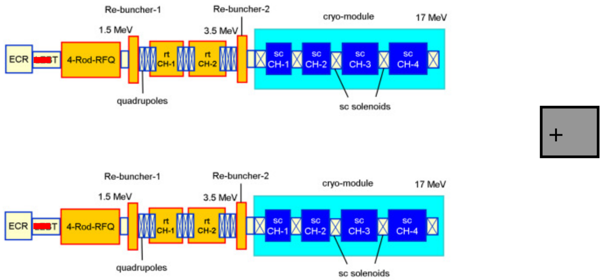
Operational injector 1: RF + PS + beam ON



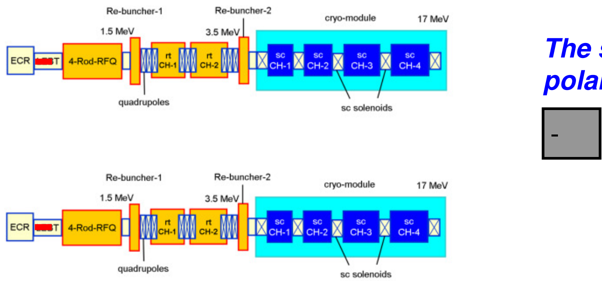
Warm stand-by injector 2: RF+ PS ON, beam OFF (on FC)

❷ A failure is detected anywhere

Beam is stopped in injector 1 by the Machine Protection System @t_0



❸ The failure is localized in injector

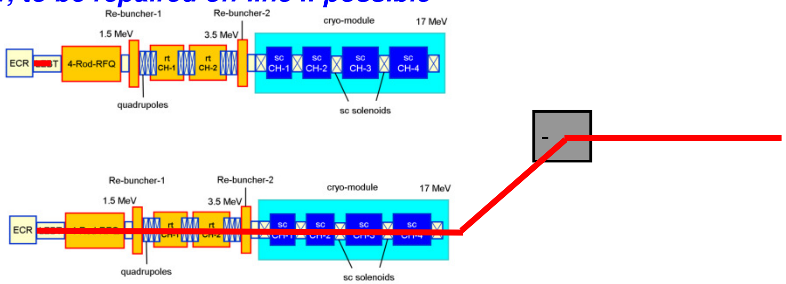


The switching magnet polarity is changed (~1s)

Need for an efficient fault diagnostic system !

❹ Beam is resumed

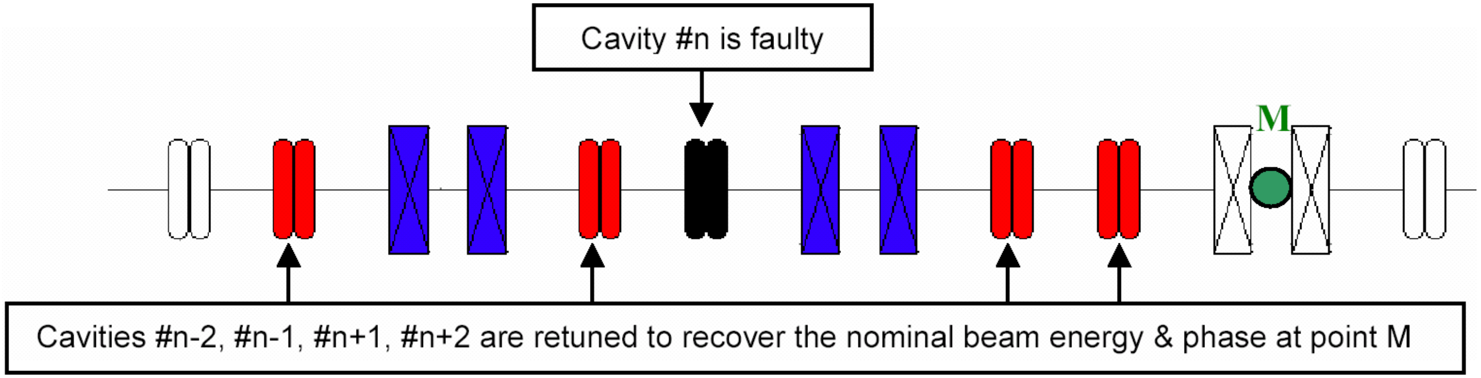
Failed injector 1, to be repaired on-line if possible



Injector 2 operational (@t_1 < t_0 +3sec)

Strategy for a fault case in the main linac

- Based on the **local compensation** concept
  - If a SRF cavity system fails & nothing is done → beam is lost ($\beta<1$)
  - If adjacent cavities operation points are properly retuned → nominal beam is recovered



- Such a scheme has been demonstrated at the SNS, and requires in MYRRHA:
  - **Independently-powered** RF cavities
  - **Operation margins** on accelerating fields and RF power amplifiers (typically +30%)
  - Tolerant beam dynamics design, with especially large **acceptance**
  - **Fast fault-recovery procedures** to perform the retuning within 3 seconds

Fast fault-recovery procedure

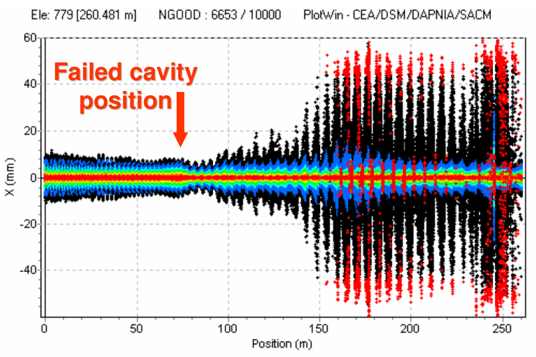


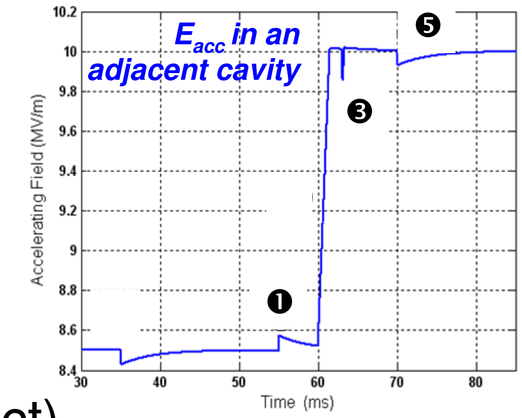
Figure 12 : Transverse beam distribution at 220 µs, in red are plotted the losses

❶ A failure is detected anywhere

→ Beam is stopped by the MPS in injector at t_0

❷ The fault is localized in a SC cavity RF loop

→ Need for an efficient fault diagnostic system

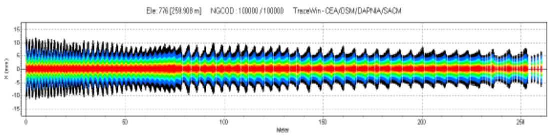


❸ New field & phase set-points are updated in cavities adjacent to the failed one

→ Set-points previously determined at the commissioning & possibly stored in the LLRF systems FPGAs

❹ The failed cavity is detuned (to avoid the beam loading effect)

→ Using the Cold Tuning System



❺ Once steady state is reached, beam is resumed at $t_1 < t_0 + 3\text{sec}$

→ Failed RF cavity system to be repaired on-line if possible

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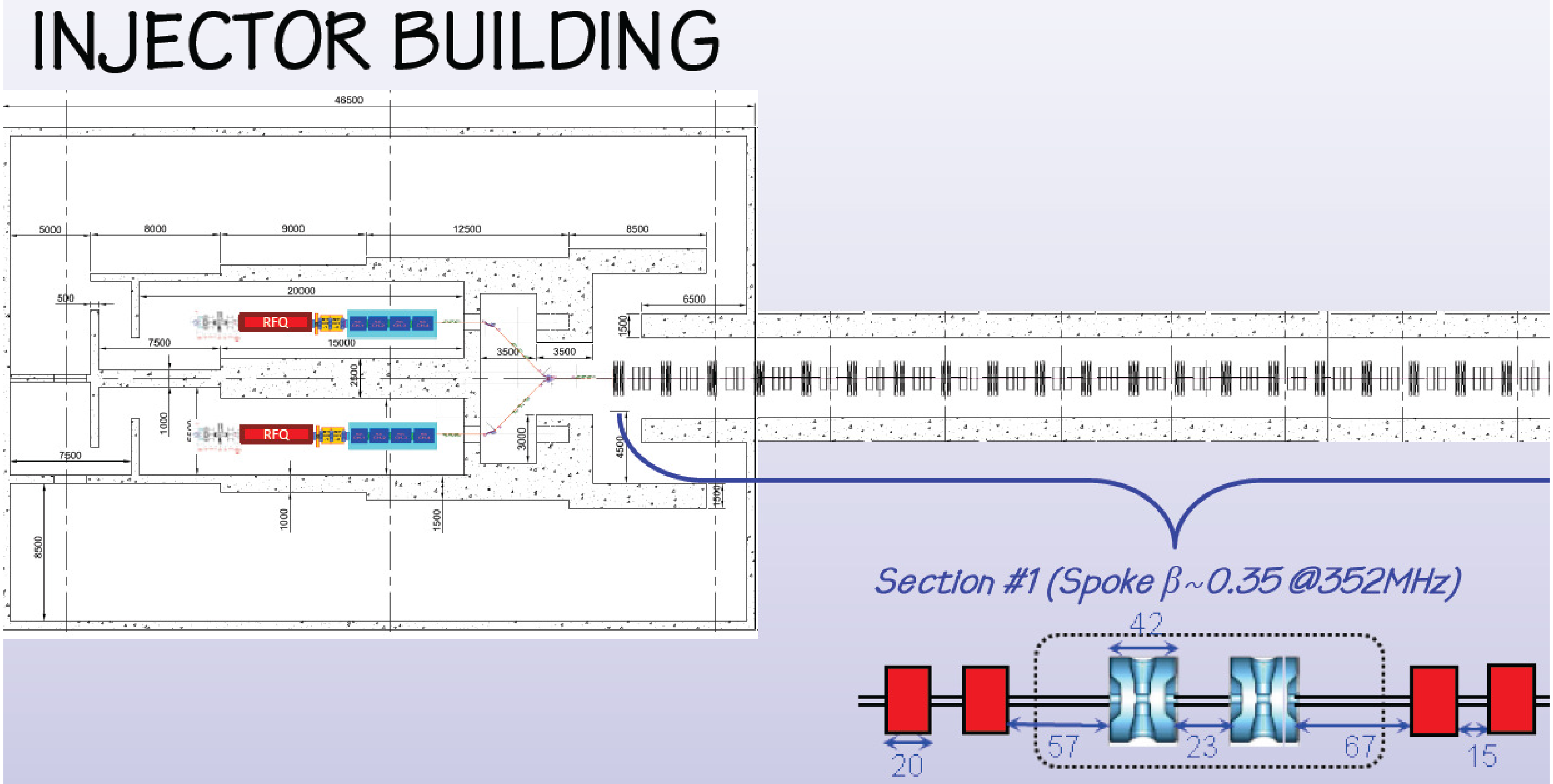
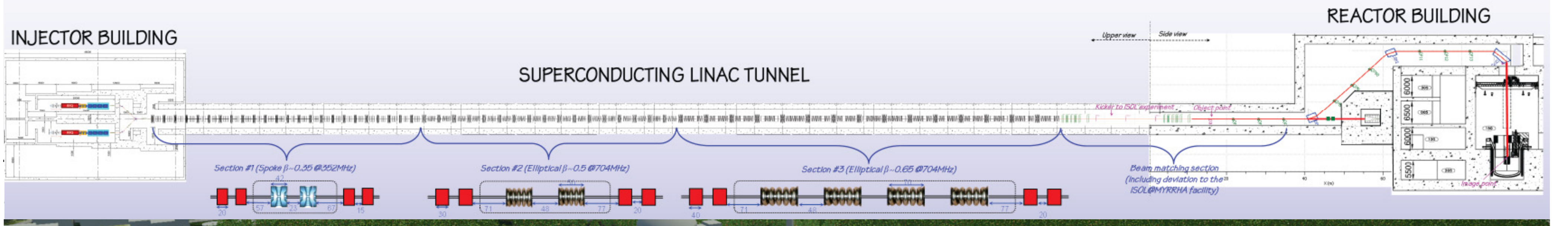
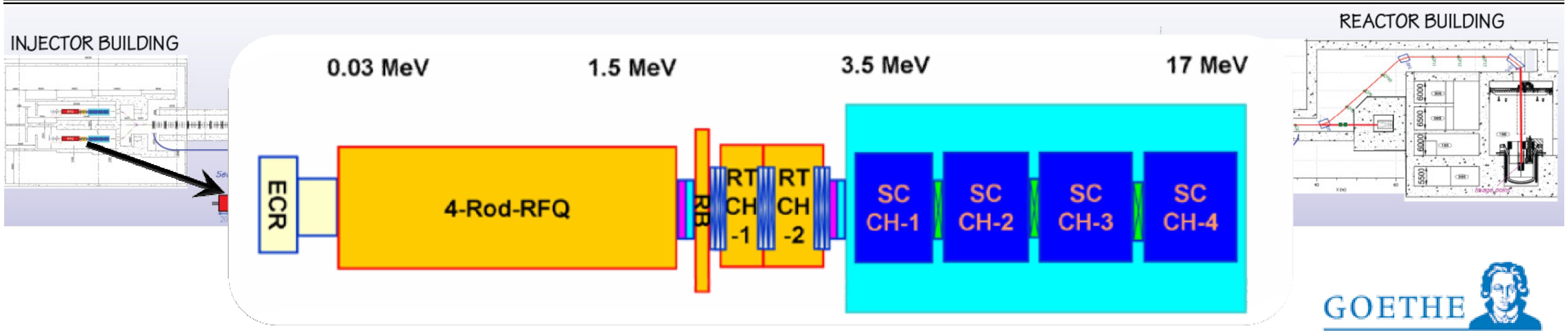
Layout of the MYRRHA linac



Layout of the MYRRHA linac

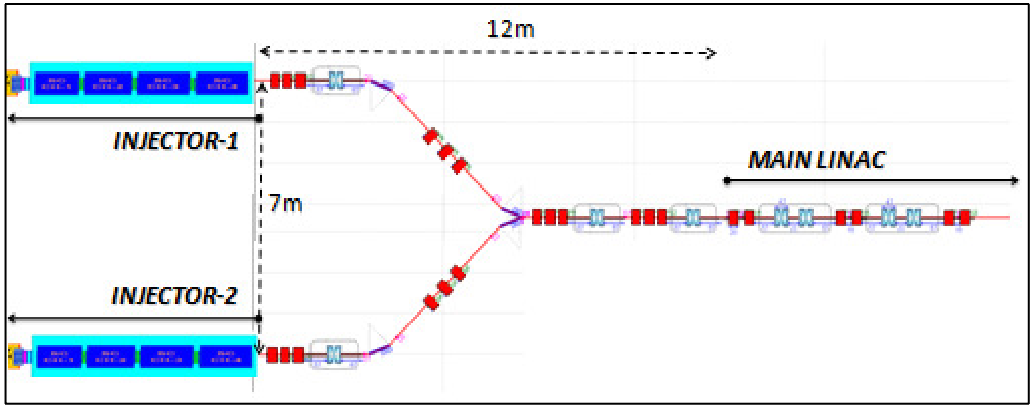


The 17 MeV MYRRHA injector

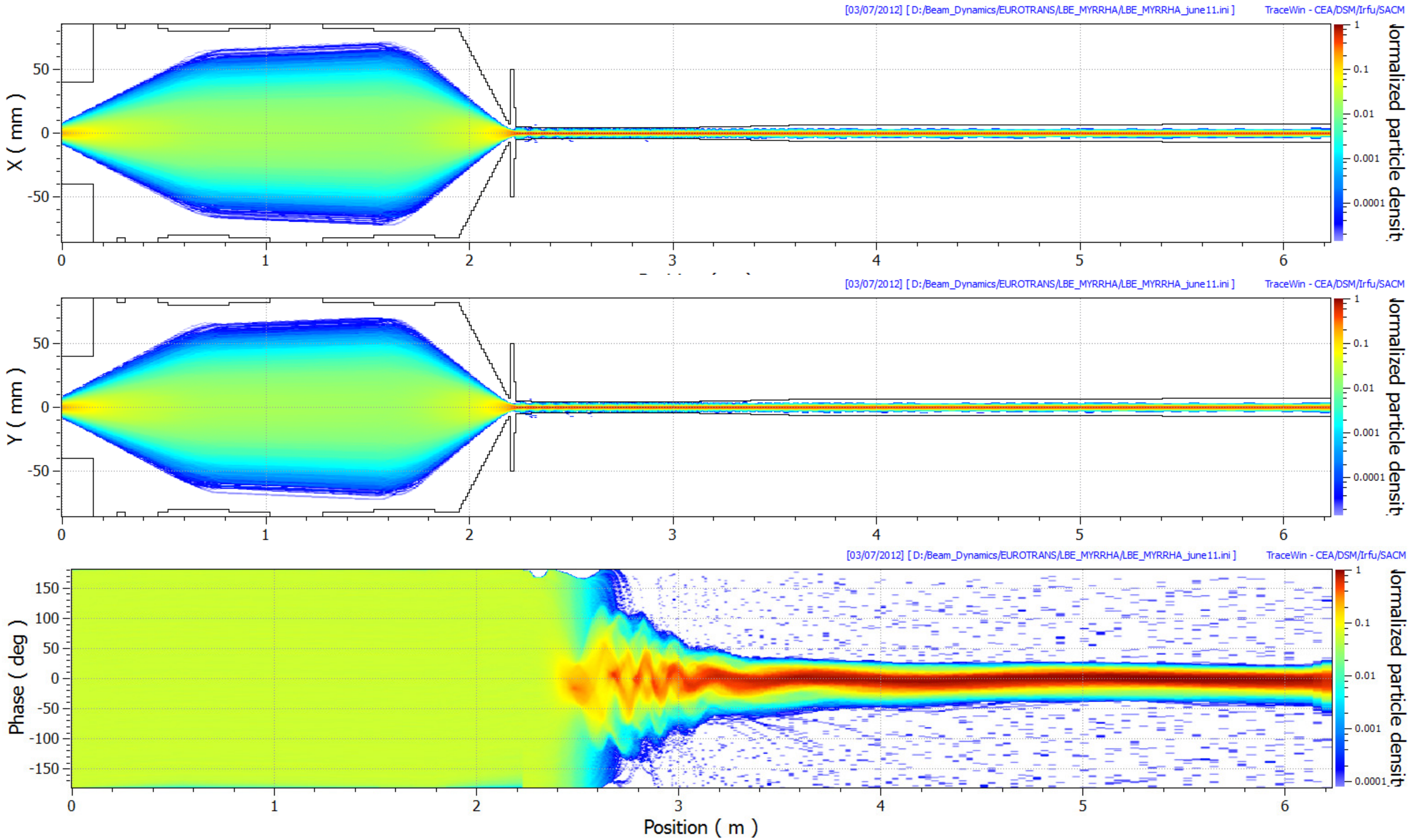


GOETHE UNIVERSITÄT FRANKFURT AM MAIN

- ECR proton source (5 mA, 30 kV) + magnetic LEBT (L=2m)
- **4-rod RFQ 176 MHz** 1.5 MeV (Kilp = 1.0, V = 40kV, P < 25kW/m, L=4m)
- 176 MHz booster composed with **6 CH cavities** (2 Cu + 4 SC, L=7m)
- Unconventional but **very efficient solution** (low nb of elements, energy gain >1 MeV/m)
- **“Double-branch” MEBT** to connect the 2 injectors to the linac, including especially 2 achromatic deviations w/ a common switching magnet and 4 SC bunchers for long. matching

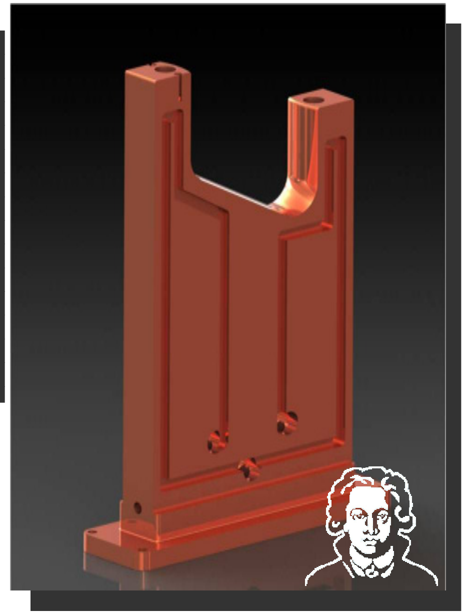


Beam dynamics in LEBT + RFQ

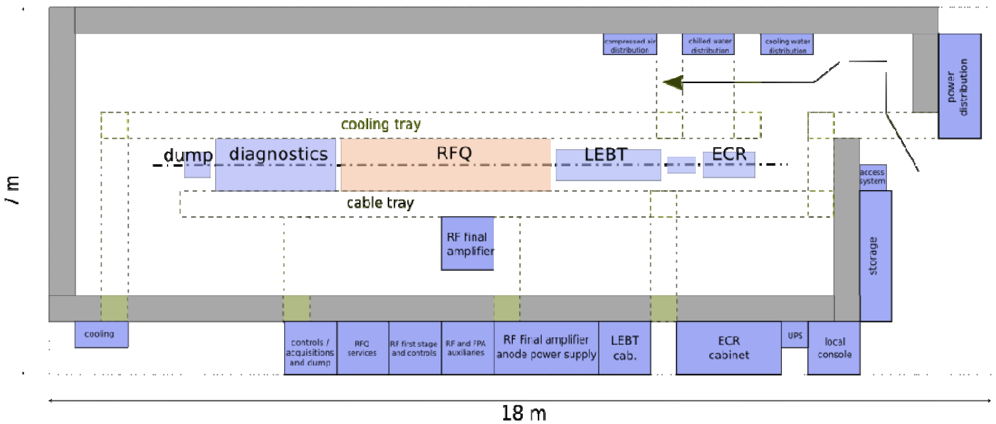


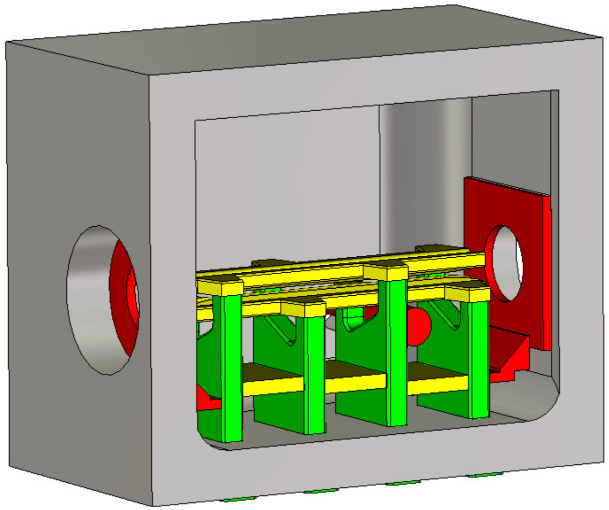
Related R&D → Source & RFQ

- **R&D on the MYRRHA 4-rod RFQ**
  - ✓ Inspired from the SARAF experience
  - ✓ **Enhanced reliability** by:
    - decreased voltages and power levels
    - improved silver-plated tuning plates
    - optimized cooling schemes for stems and rods
  - ✓ Construction of a **short test section** to be tested at nominal power in 2012/2013



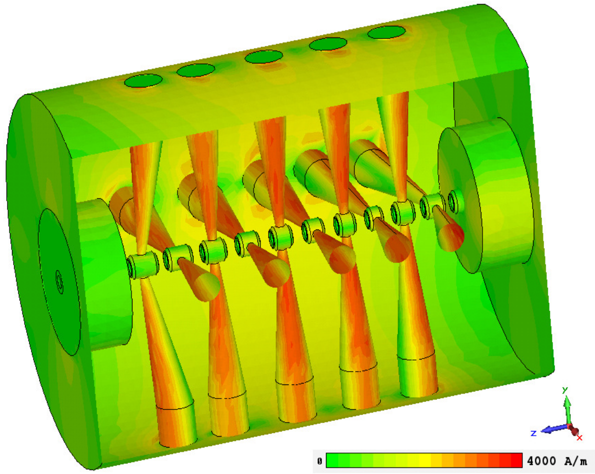
- **MYRRHA full injector test stand in construction at UCL**
  - ✓ Source in 2013, RFQ in 2014



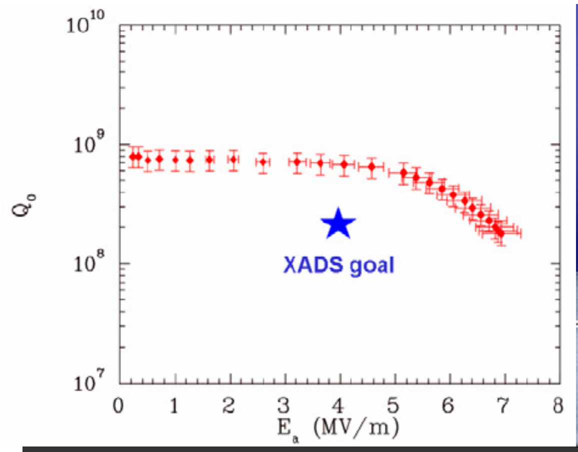


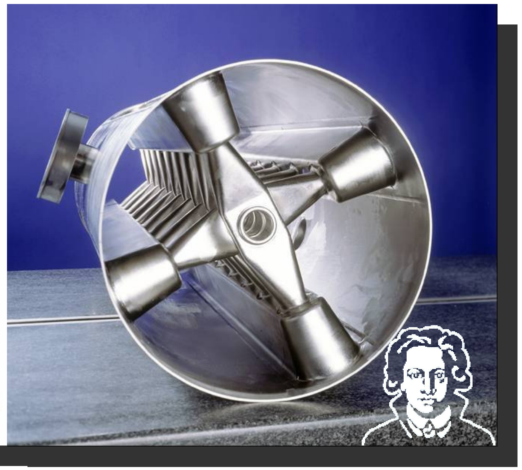
Related R&D → 176 MHz CH booster

- **R&D on room-temperature CH cavities**
  - ✓ Detailed design of the 2 MYRRHA cavities
  - ✓ Construction of a **short test section** to be tested at nominal power in 2013

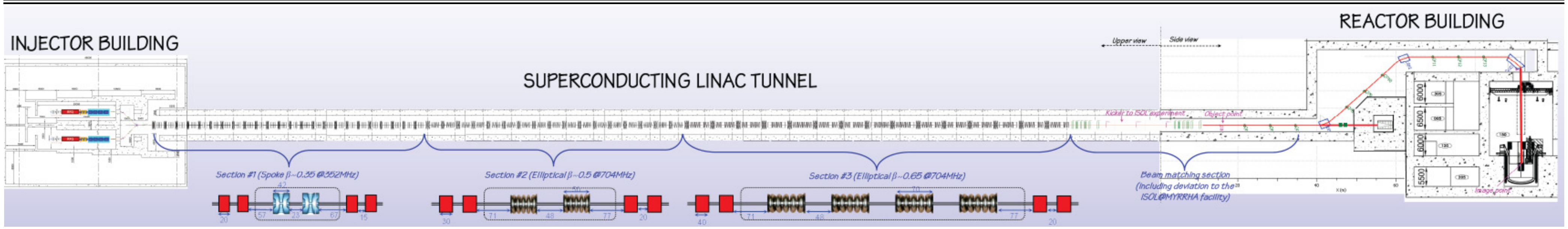


- **R&D on superconducting CH cavities**
  - ✓ Detailed design of the 4 MYRRHA cavities
  - ✓ Construction of a **new prototype cavity** to be RF tested in 2012/13, and with beam at GSI in 2014/2015





The 600 MeV MYRRHA main linac



- **Spoke** 352 MHz SC cavities × 48 (1 family)
- **Elliptical** 704 MHz SC cavities ×94 (2 families)

L=233 metres

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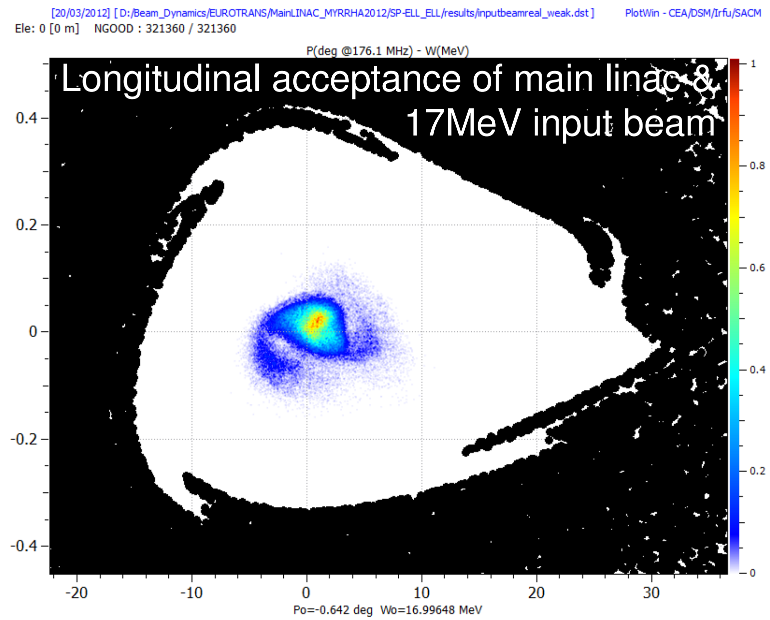
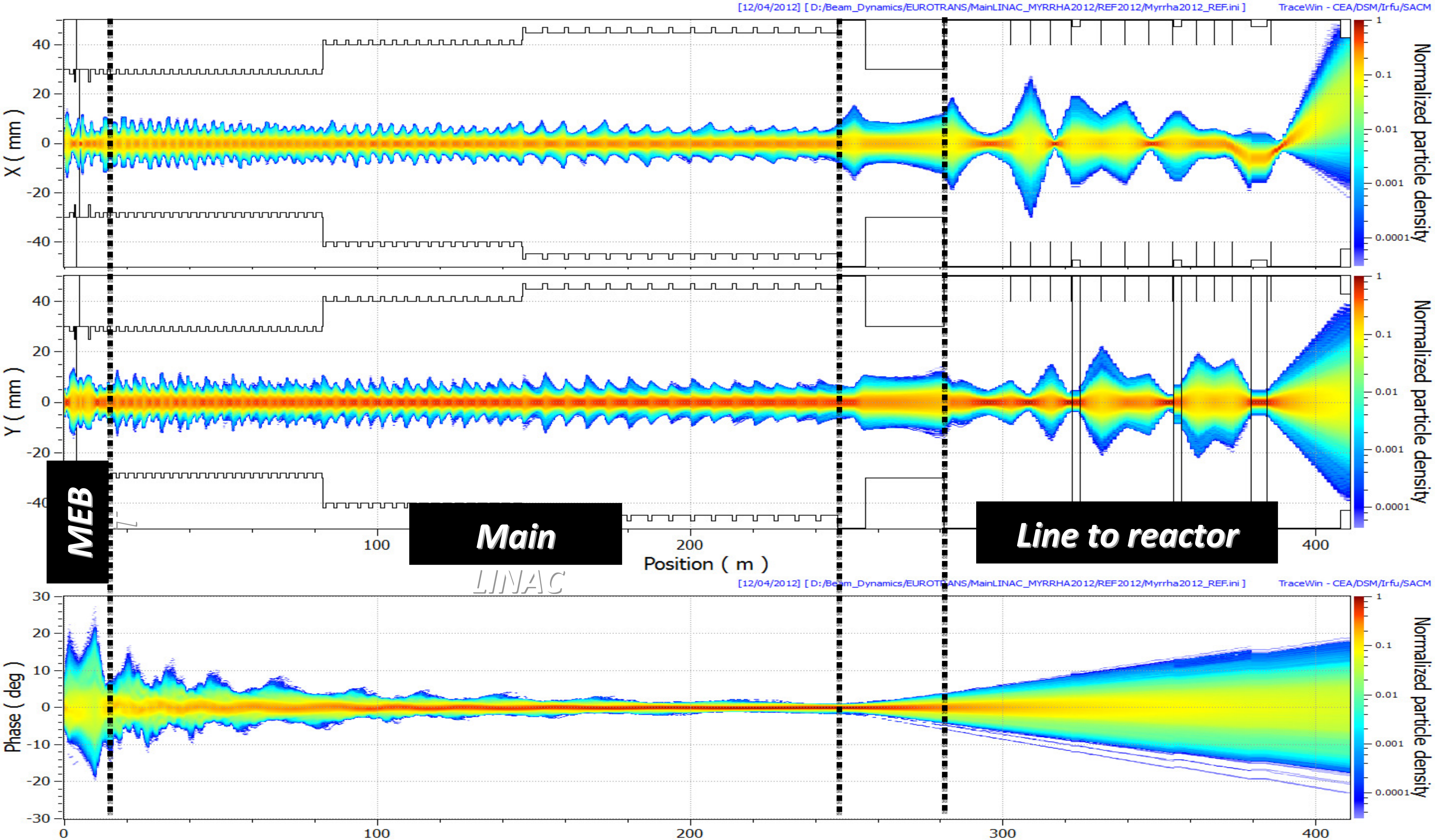
- Modularity, conservative operation points & high acceptance to **ensure fault-tolerance**

Section #	#1	#2	#3
E_{input} (MeV)	17.0	80.8	183.9
E_{output} (MeV)	80.9	183.9	600.0
Cav. technology	Spoke	Elliptical	
Cav. freq. (MHz)	352.2	704.4	
Cavity geom. β	0.35	0.47	0.65
Nb of cells / cav.	2	5	5
Focusing type	NC quadrupole doublets		
Nb cav / cryom.	2	2	4
Total nb of cav.	48	34	60
Nominal E_{acc} (MV/m)	6.2	8.2	11.0
Synch. phase (deg)	-40 to -19	-38 to -15	
Beam load / cav (kW)	1.5 to 7.5	2.5 to 17	14 to 32
Section length (m)	68.6	63.9	100.8

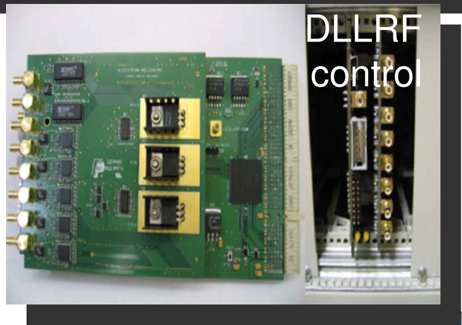


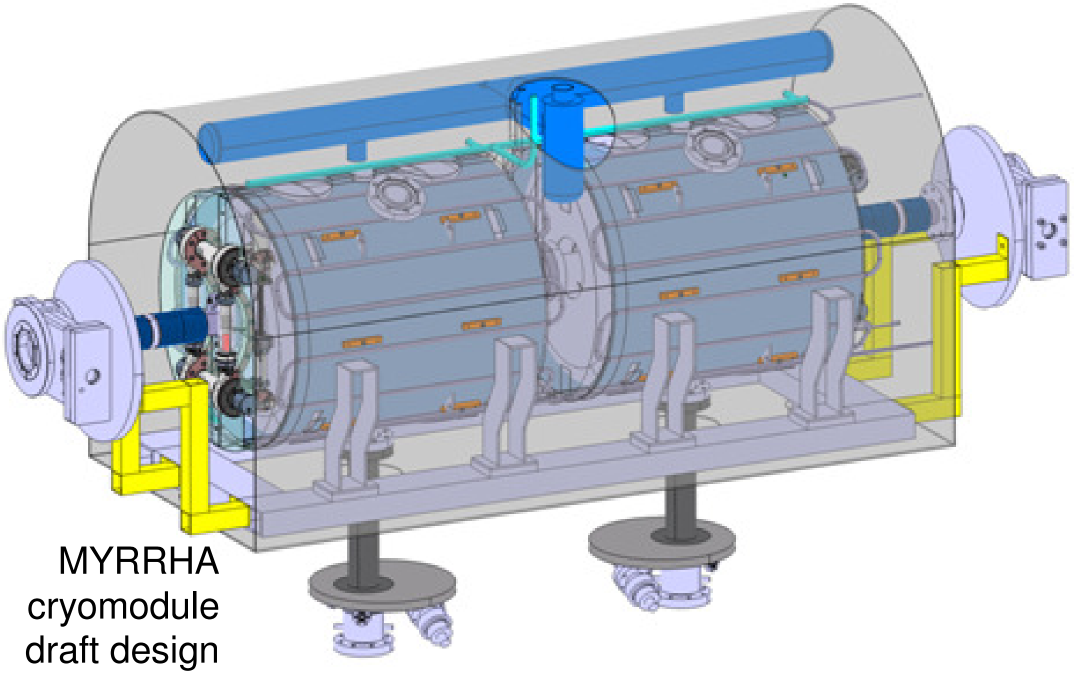
Beam dynamics in MEBT + MAIN LINAC + HEBT



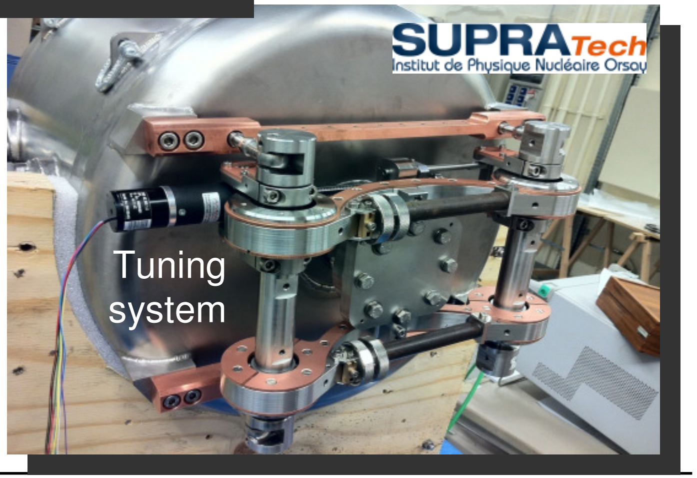
Related R&D → 352 MHz spoke cavities

- **Prototyping** of spoke cavities and ancillaries
- **Detailed design** for MYRRHA:
  - ✓ Cavity (prototype test in 2013)
  - ✓ Cryomodule (prototype test in 2015/2016)



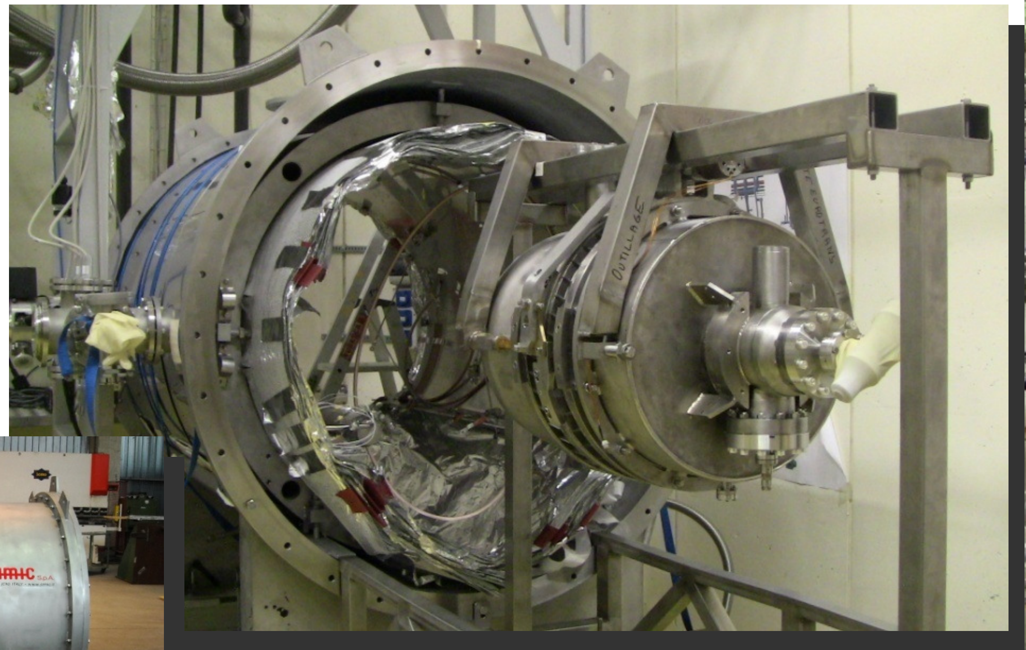


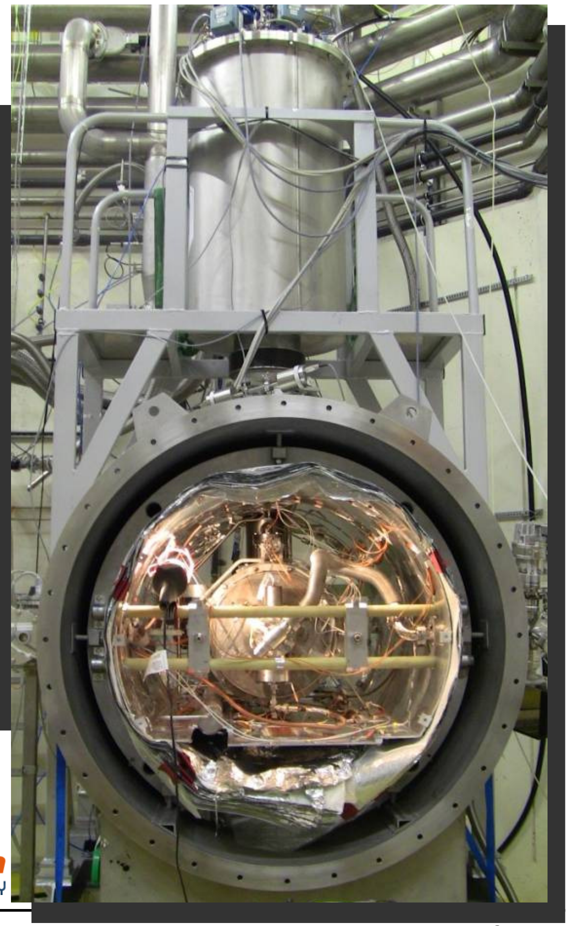
MYRRHA
cryomodule
draft design



Related R&D → 704 MHz elliptical SC cavities

- **Construction** of a β=0.5 prototype cryomodule
- **Commissioning** at low RF power in 2011/2012, and at 80 kW early 2013
- Is being used as a **test bench for reliability-oriented experiments** (fault-recovery procedures, smart regulation systems, reliability enhancement…)





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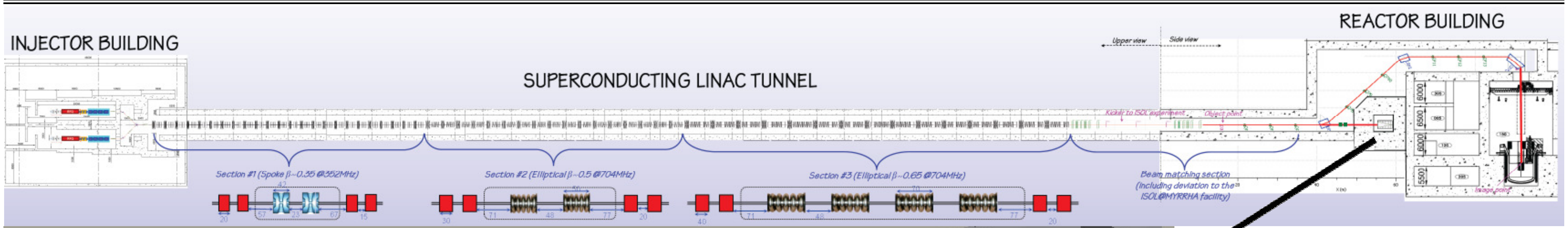
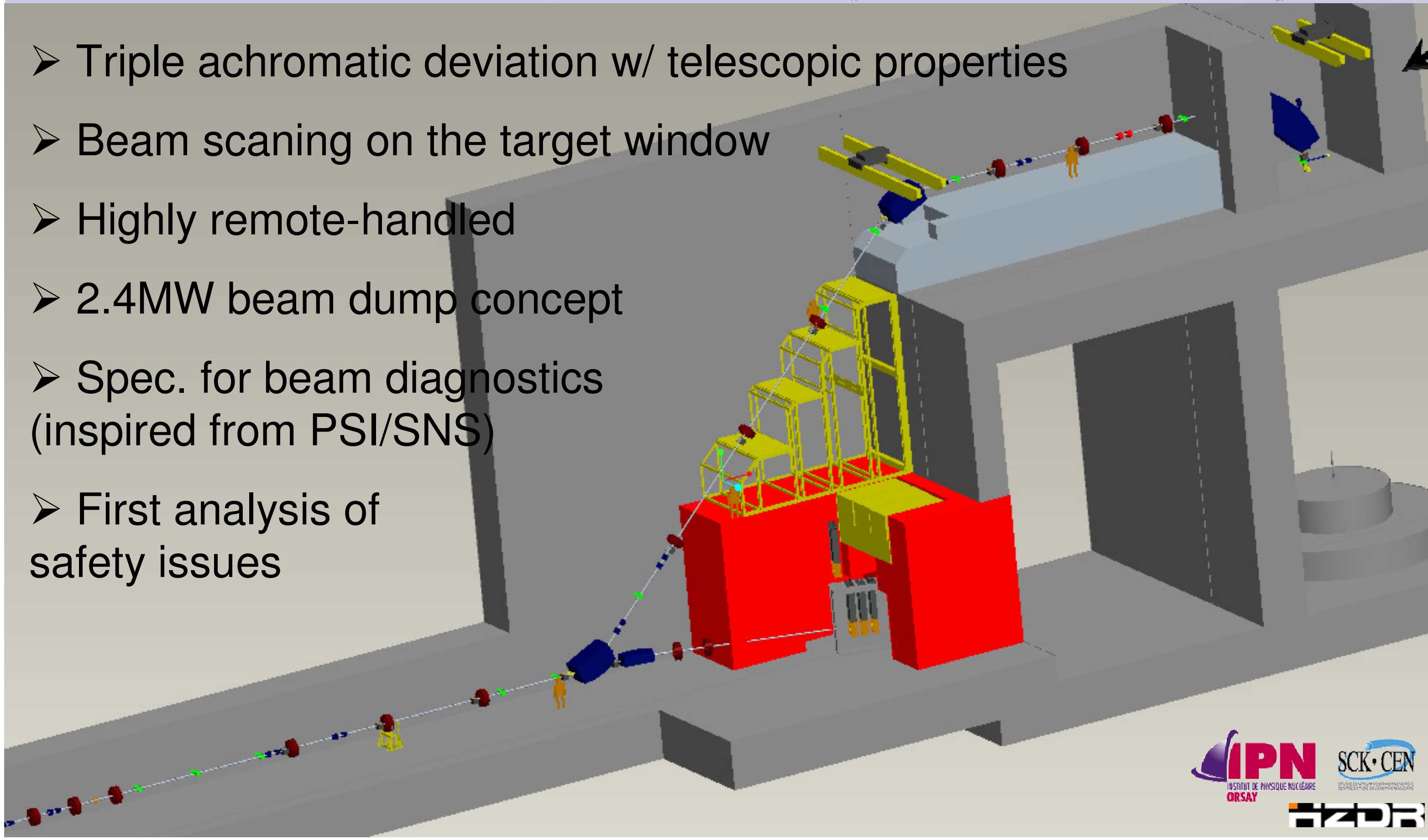
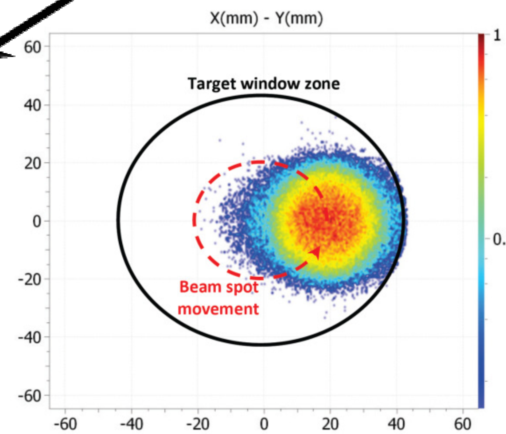
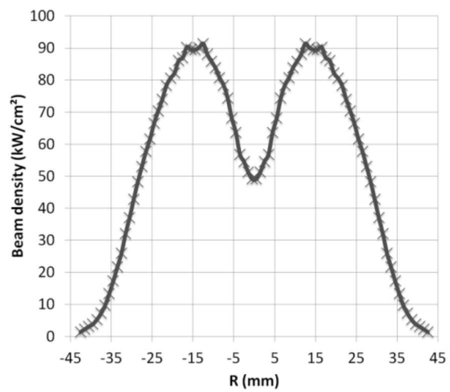
The MYRRHA final beam line



- Triple achromatic deviation w/ telescopic properties
- Beam scaning on the target window
- Highly remote-handled
- 2.4MW beam dump concept
- Spec. for beam diagnostics (inspired from PSI/SNS)
- First analysis of safety issues

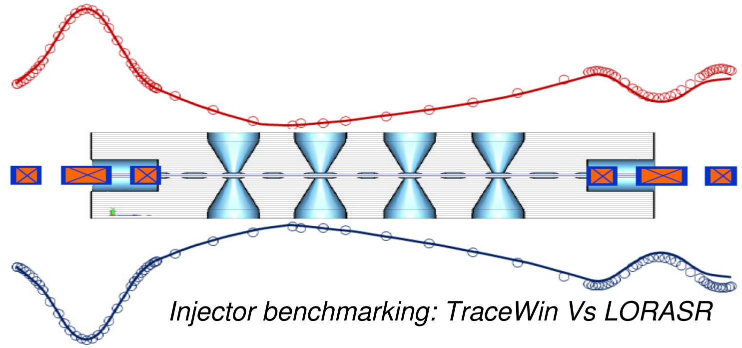


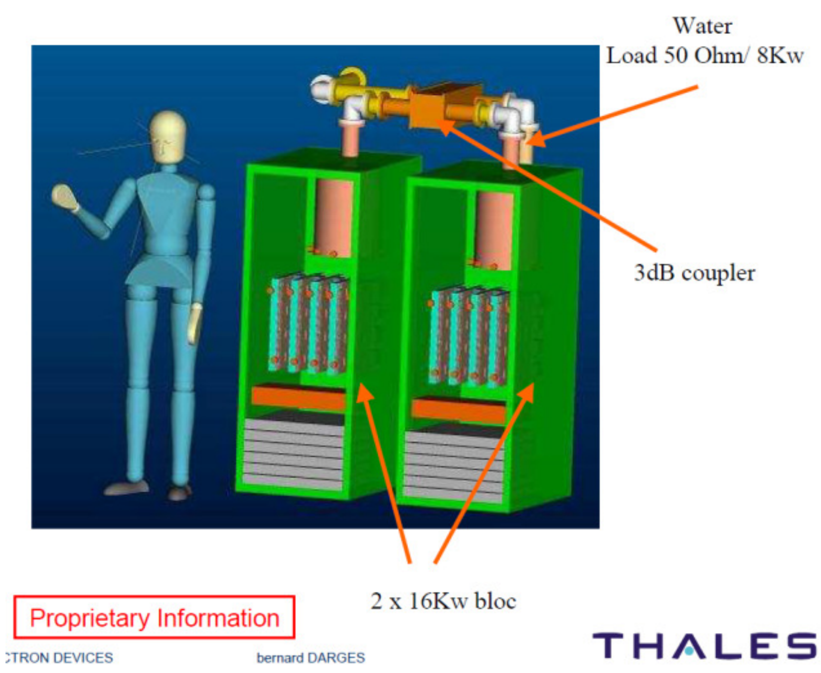




Other R&D activities

- Development of a full **reliability model**
  - ✓ Preliminary results show that the goal of MTBF=250h should be reachable
  - ✓ 3 years of commissioning is foreseen at least to learn & improve machine operation
- **Beam dynamics** simulations
  - ✓ Benchmarking (e.g. TraceWin/Lorasr)
  - ✓ Optimisation of beam behaviour in main linac under nominal & fault operation
  - ✓ Start-to-end & Monte-Carlo error studies
- Design of the **2K cryogenic system**
- 700MHz **solid-state** amp. development
- Spec. for Instrumentation & Control
- Buildings design, cost analysis…





1. Introduction
2. The P&T strategy
3. The European ADS project: MYRRHA
4. ADS accelerator specificities
5. The MYRRHA accelerator R&D

6. Conclusion

Summary

- **Nuclear waste management** is a complex (& long-term) issue in a much more complex (& shorter-term) hazard: sustainable energy & global warming

- **MYRRHA** = unique opportunity to demonstrate the ADS technology in a high-power scale

- At the end of the EURATOM FP7 projects (CDT, FREYA, **MAX**), the goal is to reach a sufficient level of design to be able to launch a construction phase for MYRRHA in 2015

- The **ADS accelerator reference scheme** is based on a 600 MeV, 4 mA cw superconducting proton LINAC

- R&D is focused on the **reliability issue**. This may bring substancial impact for availability optimisation in future accelerator projects featuring high power proton beams.

Thank you for your attention !

COORDINATOR

http://ipnweb.in2p3.fr/MAX/

http://myrrha.sckcen.be/

cnrs IN2P3 Les deux infinis

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