Role of Nuclear Energy in the Future Energy Mix and Needs for R&D in Closing the Fuel Cycle

MYRRHA project and its Accelerator Programme

Prof. Dr. Hamid AÏT ABDERRAHIM

Deputy Director General of SCK•CEN

Director of the MYRRHA Project

haitabde@sckcen.be or myrrha@sckcen.be

Seminar Department of Physics & Astronomy of Uppsala University
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STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

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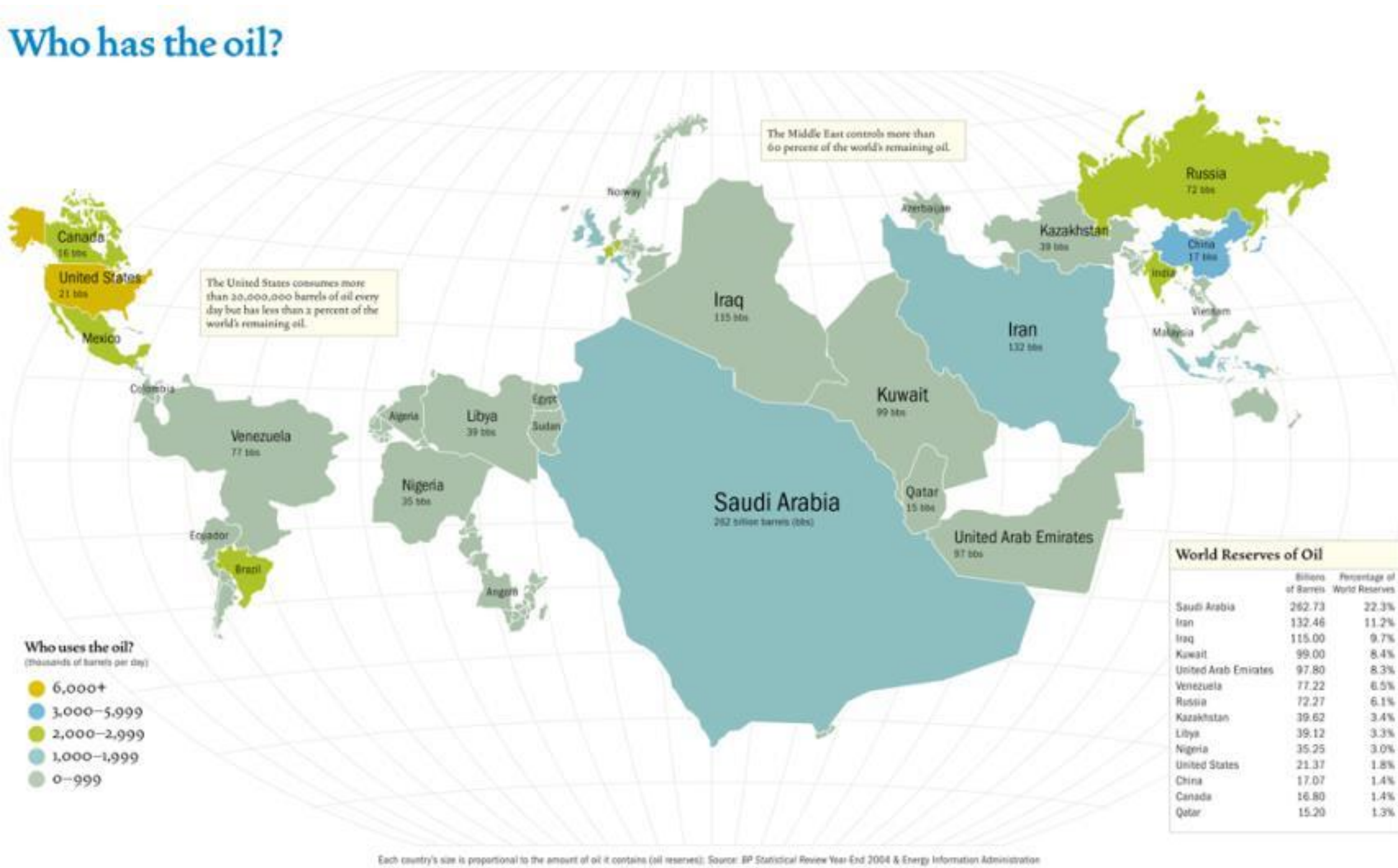
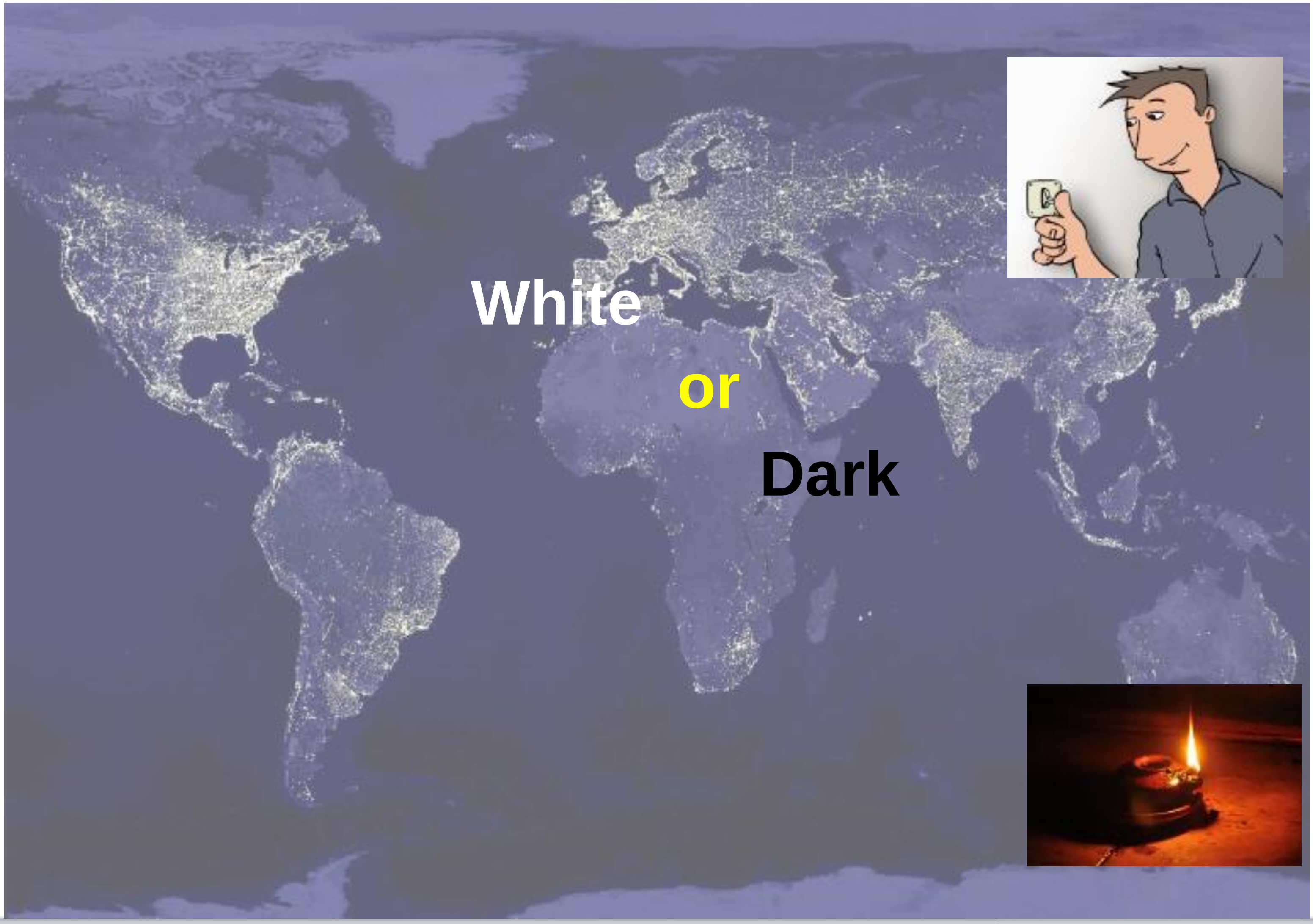
- Role of Nuclear Energy in the Future Energy Mix
- The EC Partitioning & Transmutation strategy for HLW management
- MYRRHA Project and its Accelerator programme
- Conclusion

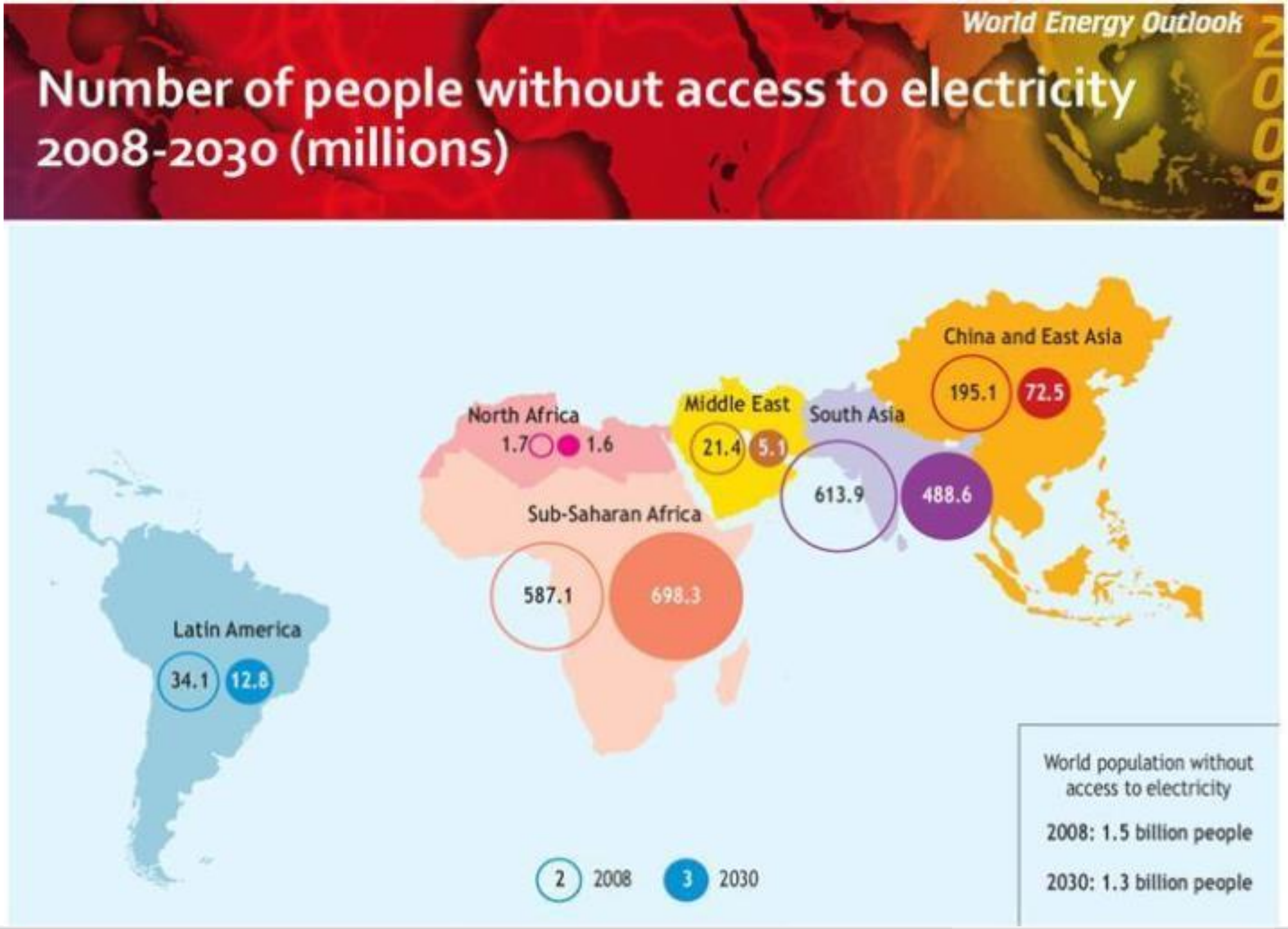
Energy challenges :
geopolitical considerations – Who has the oil?



Energy challenges :
What's the colour of electricity? Green? Red? Blue?...



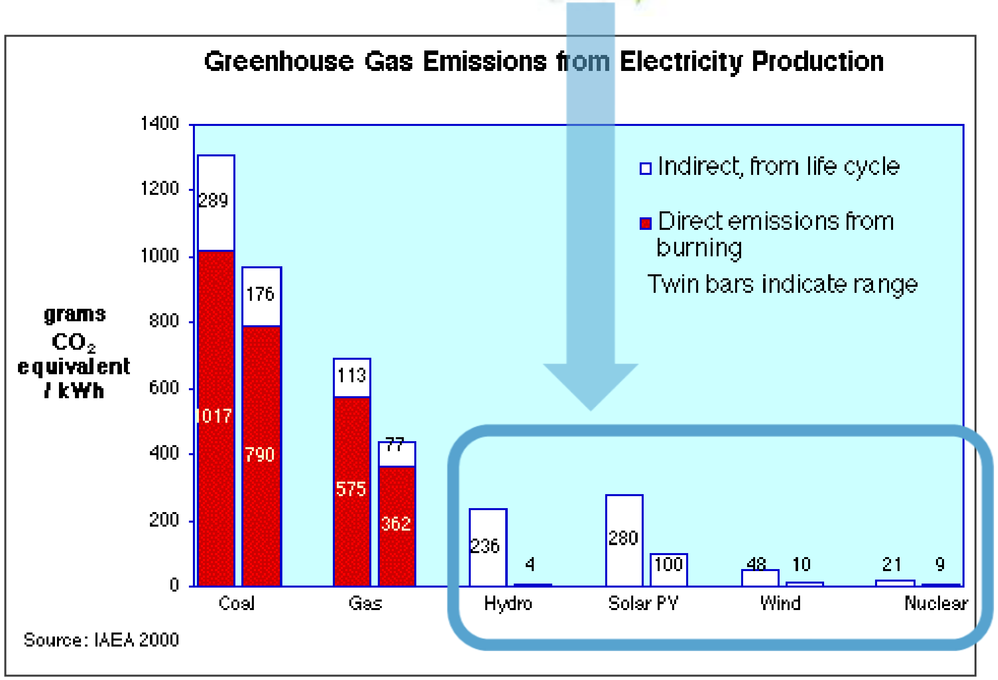
Energy challenges :
Large fraction of the world population has no access to access…and likely will not



Energy challenges :
Will the energy saving, save the world ?

	2010	2030	2050
Pop. OECD (mio)	1.200	1.400	1.500
Energy Demand (oet/cap.)	5.5	3e	2.8
Total Energy Consumption OECD (mio oet)	6.600	↓ 4.200	4.200
Pop. Non-OECD (mio)	5.400	6.700	7.500
Energy Demand (oet/cap.)	1	2	2.8
Total Energy Consumption Non-OECD (mio oet)	5.400	↑ 13.400	↑ 21.000
TOTAL CONSUMPTION (mio oet)	**12.000**	↑ **17.600**	↑ **25.200**

Energy challenges :
invest in all CO_2 non-emitting energy sources including nuclear energy



So, future is bright for nuclear

We know what to do
Global challenges for nuclear energy today

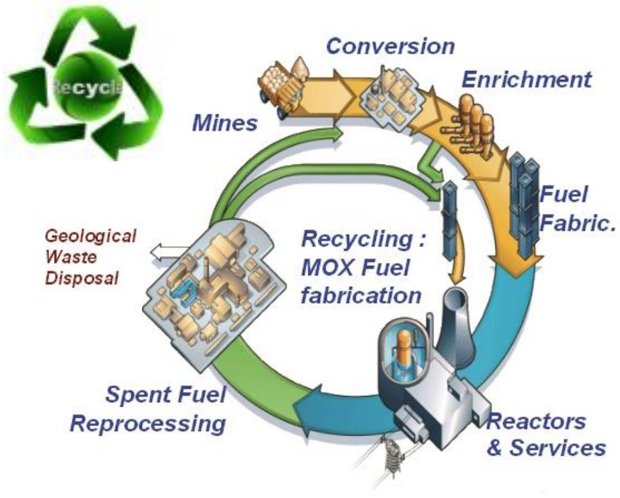
Common needs

Burning legacy of the past

Reducing cost of ultimate waste

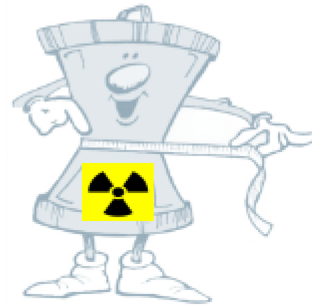
Better use of resources

Enhance Safety



To make nuclear energy sustainable and part of the energy-mix of tomorrow

SNETP
Sustainable Nuclear Energy Technology Platform



nuclear waste

resource utilisation

Enhanced safety

proliferation risk

We got a worldwide guideline for the nuclear technology

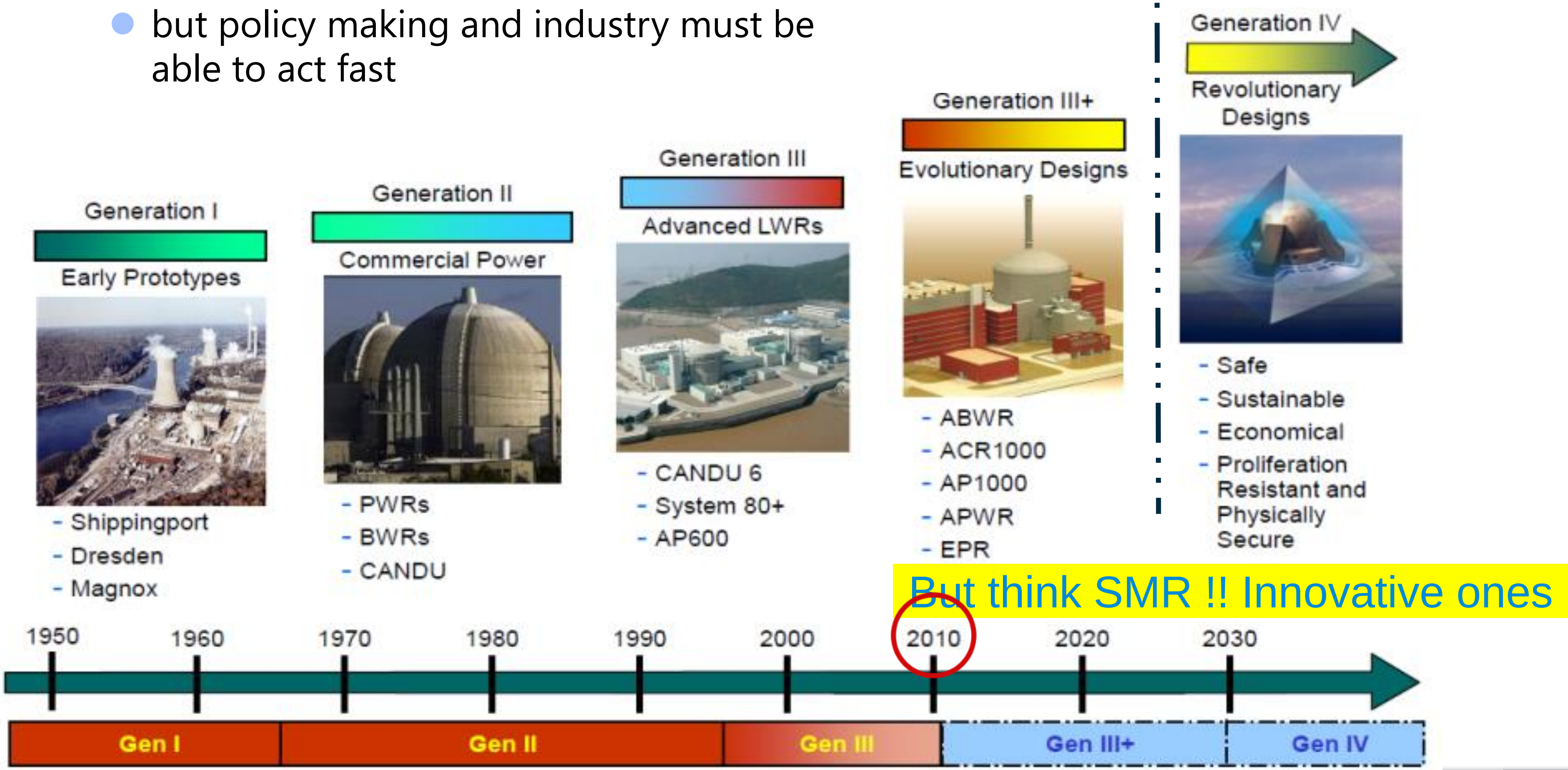
By Gen.IV Internal Forum but this can be updated

GEN II, III, III+ can do the CO_2 job by 2050

- nuclear x3?: technology exists: need for ~20 plants to be on-line/year til 2050
- but policy making and industry must be able to act fast

Fast neutrons

- reduce waste legacy
- maximise resources



Turn R&D into :
Economic valorisation may be with actors not coming from the sector

Développement de petits réacteurs modulaires
(50 – 300 MW)

Mini nuclear reactors
The Economist Dec 9 2010

A new paradigm for power generation (1)

Bill Gates, one of the richest men in the world, suggests that we use nuclear power plants to reach a goal of zero carbon output.

Toshiba and TerraPower aim to create a reactor that doesn't need to be refueled for 100 years.

It's possible Microsoft Chairman Bill Gates and Toshiba have opened dialogue to create a next-generation nuclear reactor able to run up to 100 years before it needs to be refueled, according to Japanese media reports.

Gates' TerraPower and Toshiba's Westinghouse reactor design company plan to develop the uranium-based Traveling-Wave Reactor (TWR) with 100,000 Kilowatts up to 1 million KW support.

Until something is official between the two sides, and Toshiba will continue development on a reactor that needs to be refueled once every 30 years. The Super-Safe, Small and Simple (4S) reactor is an ultra compact reactor that will likely have U.S. approval before the end of the year.

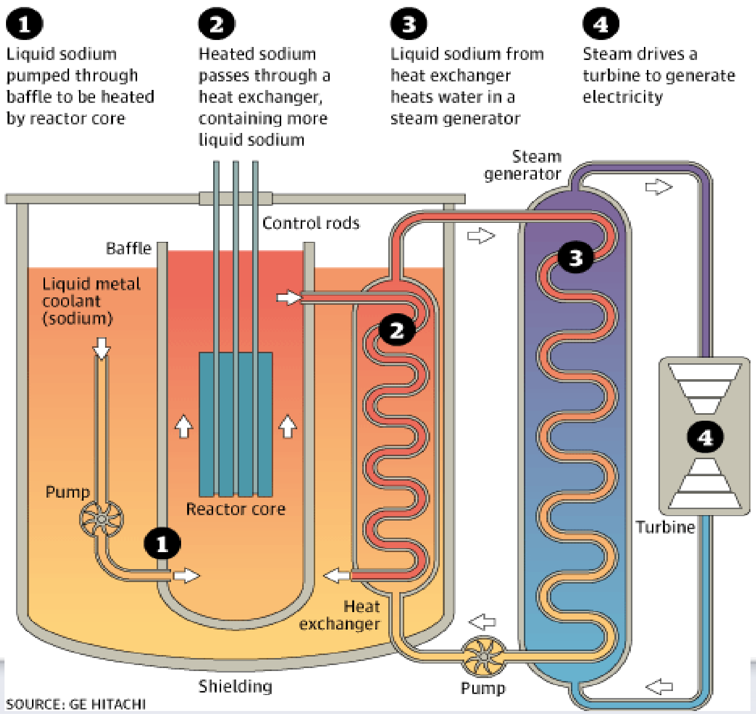
If there are no major hiccups, the reactor will be available before 2014.

Today's units need to be refueled every few years – using fuel based from depleted uranium can last significantly longer. There is special need for these mini-reactors in developing nations, analysts say, with the price tag expected to lower in the future.

A new paradigm for power generation (2)

Richard Branson urges Obama to back next-generation nuclear technology
Billionaire pushes for the technology in a letter to White House that says integral fast reactors are clean, inexpensive and safe

Richard Branson: "Obviously we urgently need to come up with a clean effective way of supplying our energy since not only are the dirty ways like oil running out but we need to do so to help avoid the world heating up". In The Guardian of July 20, 2012



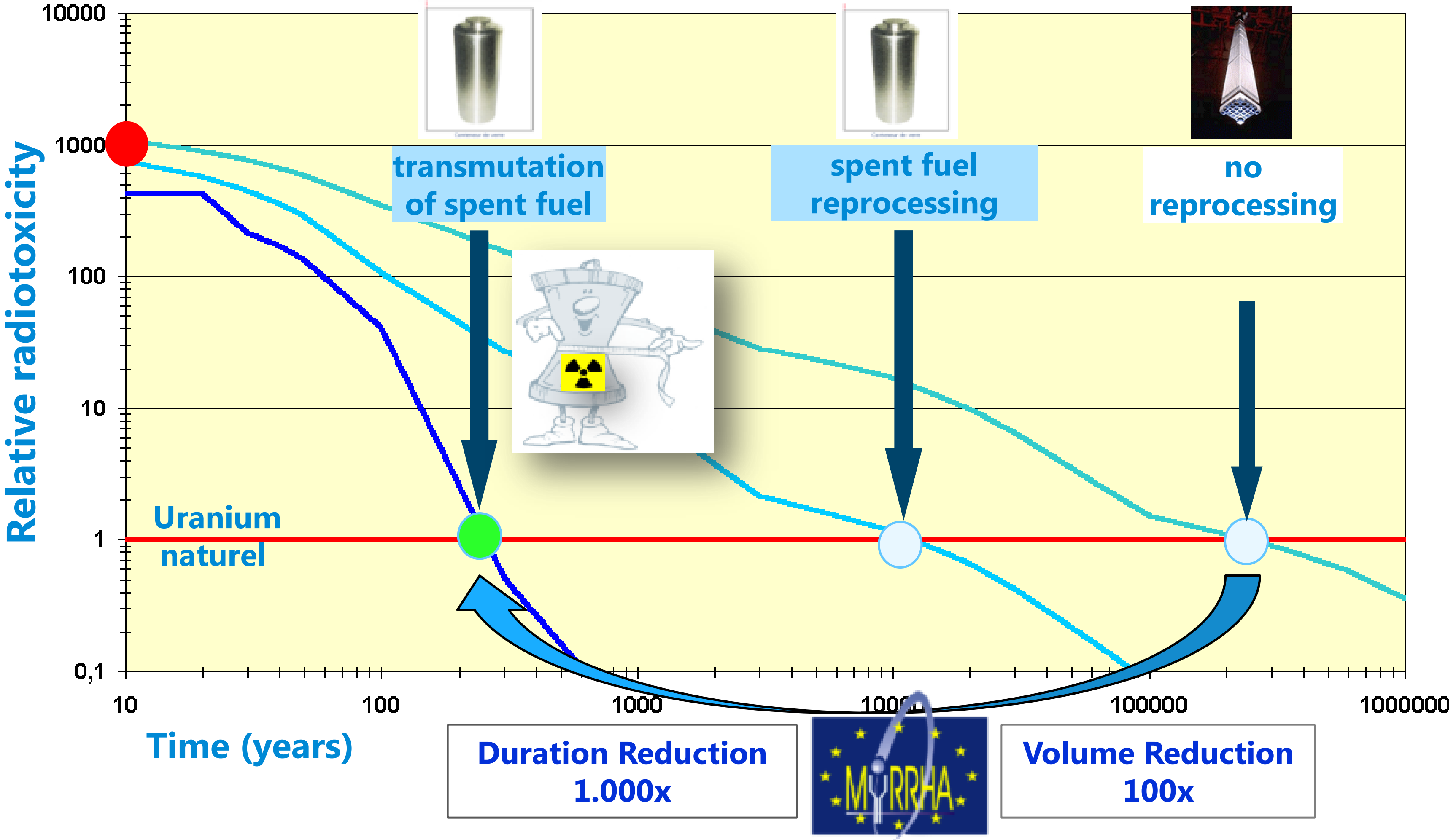
The EC Partitioning & Transmutation strategy for HLW management

High Level Waste Mgt status in the world at glance

1 ton UO_2 used fuel (50 GWd/t)

	No Recycling Once Through	Todays Recycling PUREX (La Hague)	Tomorrow Recycling
935 kg U 12 kg Pu	**Nearly 1 ton as HLW to Geological Disposal**	U + Pu recycled	U + Pu recycled
1 kg Np 0,8 kg Am 0,6 kg Cm	Presently adopted in US, SE, FIN Decision for industrial Geol. Disp., under construction	**53 kg HLW to Geolo. Disp. In vitrified waste form** Presently adopted in FR, JP, UK … No formal decision for industrial Geol. Disp. yet	**MA recycled & ~50 kg HLW to Geolo. Disp. In specific packaging** Presently R&D programme (FR, JP, EU, BE, CN, ROK, USA)
~50 kg PF (3,5 kg PFVL)	**Burden of HLW for more than 300,000 y**	**Burden of HLW for more than 10,000 y**	**Burden of HLW for ~300 y**
	Industrial scale	Industrial scale	R&D level

Come with acceptable solutions for HLW
Motivation for transmutation



Demonstration of P&T at **engineering level** at the center of the European Commission Strategy

- The EC and EU Membre States R&D activities consists of four "building blocks" (BB):

1. Demonstration of the capability to process a sizable amount of spent fuel from commercial LWRs in order to separate plutonium (Pu), uranium (U) and minor actinides (MA),
2. Demonstration of the capability to fabricate at a semi-industrial level the dedicated fuel needed to load in a dedicated transmuter, (JRC-ITU)
3. Design and construction of one or more dedicated transmuters, ➔ **MYRRHA**
4. Provision of a specific installation for processing of the dedicated fuel unloaded from the transmuter, which can be of a different type than the one used to process the original spent fuel unloaded from the commercial power plants, together with the fabrication of new dedicated fuel.

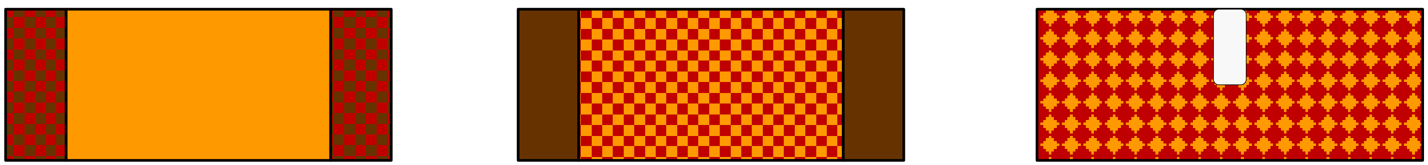
EC contributes to the 4 BB and fosters the national programmes towards this strategy for **demonstration at engineering level**.

Belgium contributes to the EC P&T strategy by focusing on BB3 through the realisation of MYRRHA as a pre-industrial ADS demonstrator and R&D facility

Three options for Minor Actinide transmutation

EU is presently considering two approaches for transmutation: via FR or ADS

FR heterogeneous	FR homogeneous	ADS

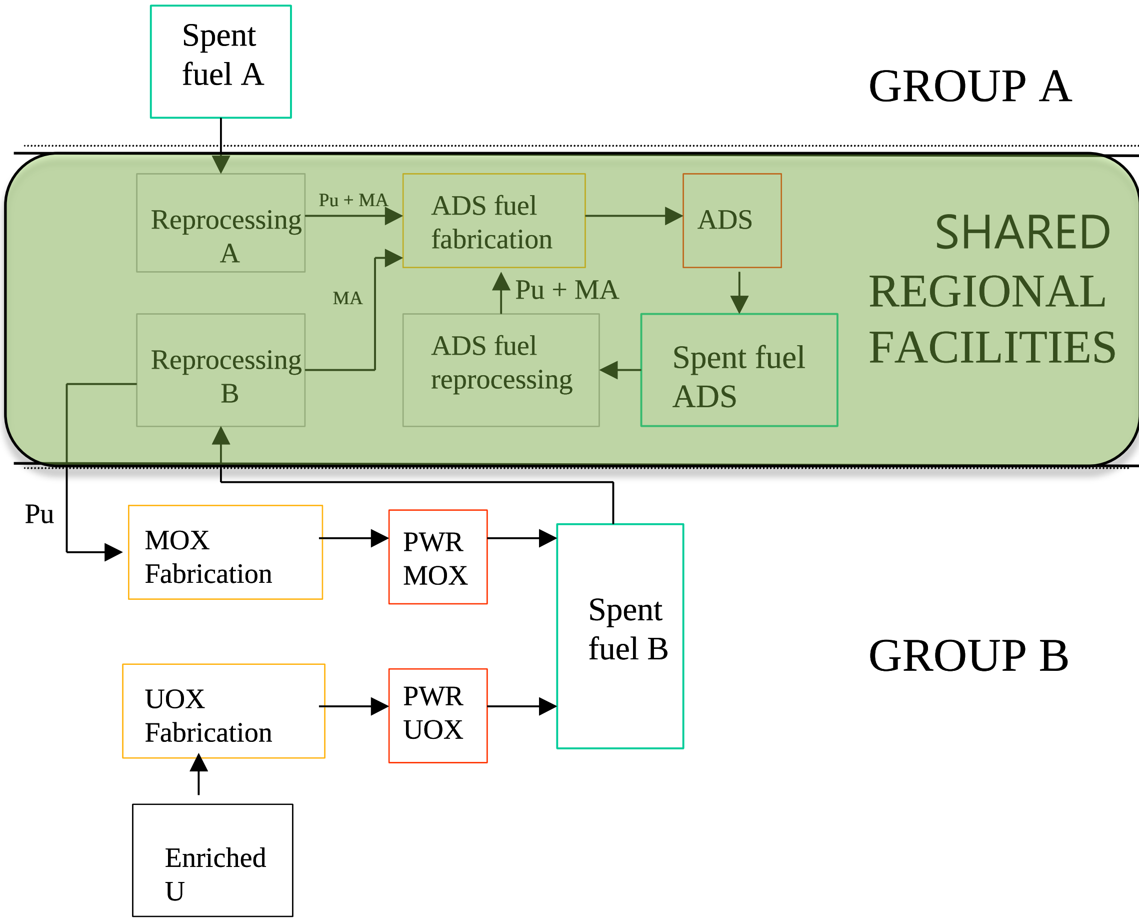


Driver fuel Blanket with MA	Fuel with MA Blanket	Fuel with MA

Core safety parameters limit the amount of MA that can be loaded in the critical core for transmutation, leading to transmutation rates of:

- FR = 2 to 4 kg/TWh
- ADS = 35 kg/TWh (based on a 400 MW_{th} EFIT design)

Even with completely different national NE policies European solution for HLW works with ADS



- ❑ **Advantages for A**
  - ADS shared with B
  - ADS burn A's Pu& MA
  - Smaller Fu-Cycle units & shared
- ❑ **Advantages for B**
  - ADS shared with B
  - ADS burn B's MA
  - A's uses B's Pu (part) as resource in FR
  - FR fleet not contam with MA's
  - Smaller Fu-Cycle units & shared

Scenario 1 objective: elimination of A's spent fuel by 2100

A = Countries Phasing Out, B = Countries Continuing

Economics evaluation need validations

- Investment – capacity needed
- Operational costs
- Fuel cycle costs
- Transportation costs
  - Spent LWR fuel
  - Homogeneous MA fuel for Fast Reactors
  - Heterogeneous MA fuel for Fast Reactors
  - ADS fuel

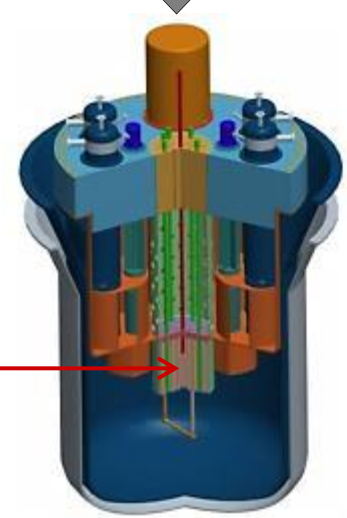
- Technological Readiness Levels are low → very hard to estimate costs
- **We need pre-industrial level demo facilities for the various stages of P&T at international level, Belgium contributes to BB3 through MYRRHA**

MYRRHA project & its Accelerator Programme

MYRRHA is an Accelerator Driven System

- Coupling of an accelerator, spallation target and reactor
  - Can operate in critical and sub-critical modes (k_{eff} = 0,95)
  - accelerator controls criticality (in ADS mode)

Accelerator	
particles	protons
beam energy	600 MeV
beam current	2.4 to 4 mA



Reactor	
power	65 to 100 MW_{th}
k_{eff}	0,95
spectrum	fast

Target	
main reaction	spallation
output	$2 \cdot 10^{17}$ n/s
material	LBE (coolant)

- MYRRHA: a Pb-Bi cooled reactor to be operated as an ADS
- The ADS needs a neutron source
- Spallation is an efficient fast neutron generating mechanism (medium energy protons)
- Rule of thumb: $P_{\text{beam}} \sim (1 - k_{\text{eff}}) P_{\text{th}}$

→ beam power of several MW !!

→ CW beam !!

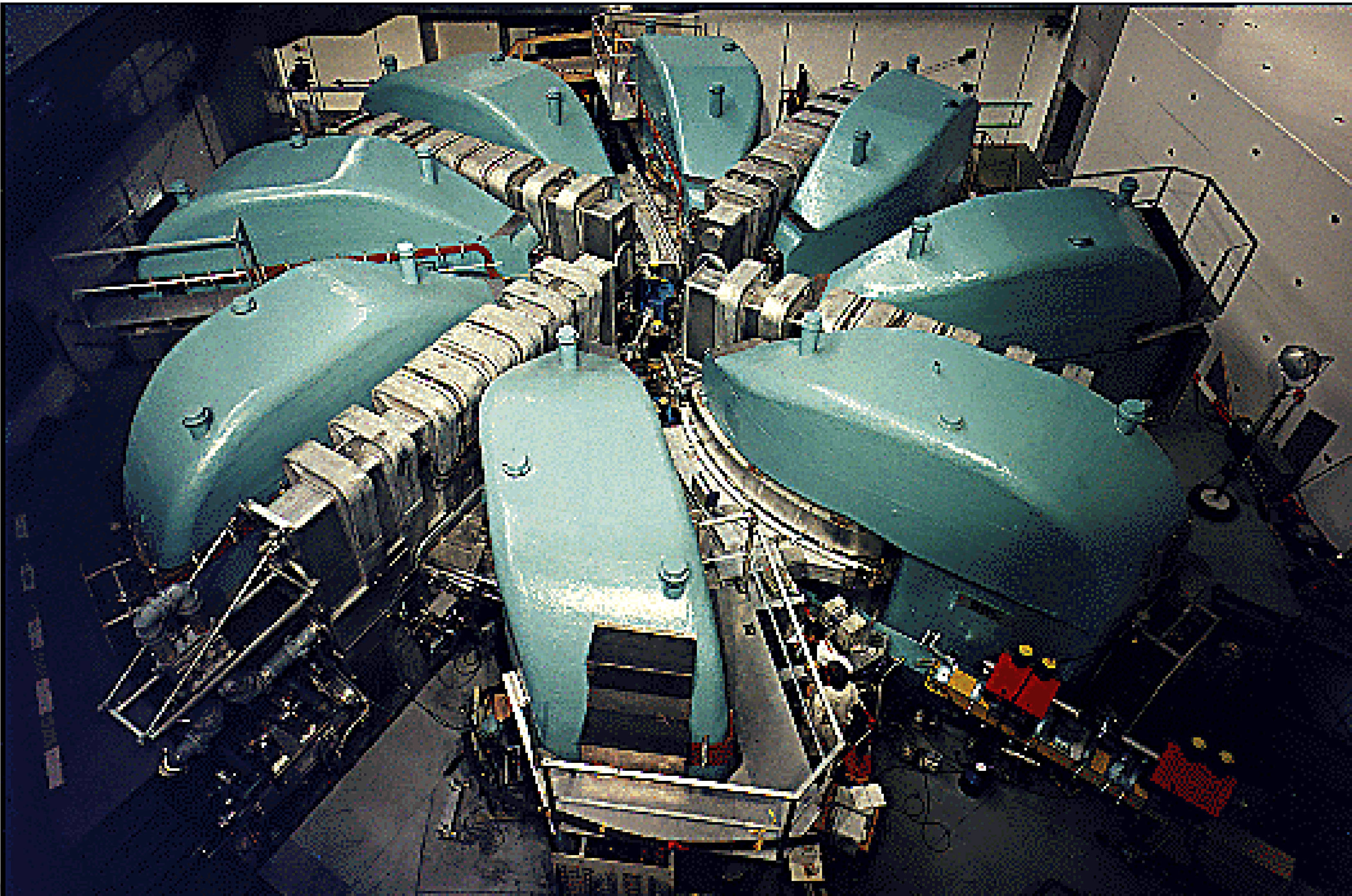
basic specifications	
particle	p
beam energy	600 MeV
beam current	4 mA
mode	CW
cycle length	3 months
beam MTBF	> 250 h

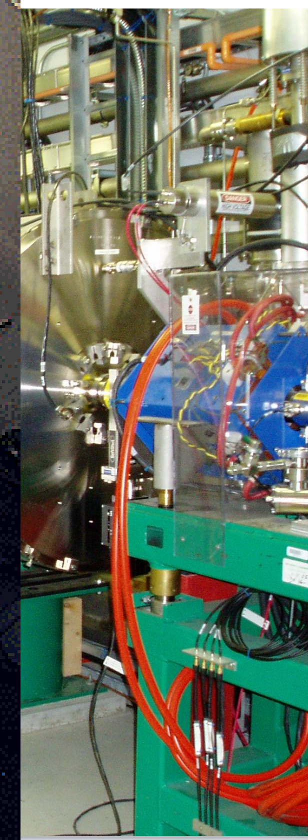
Initial challenges

- organizational
  - SCK•CEN: Reactor expertise than Accelerator
  - European context
  - European Framework Programs: an opportunity !

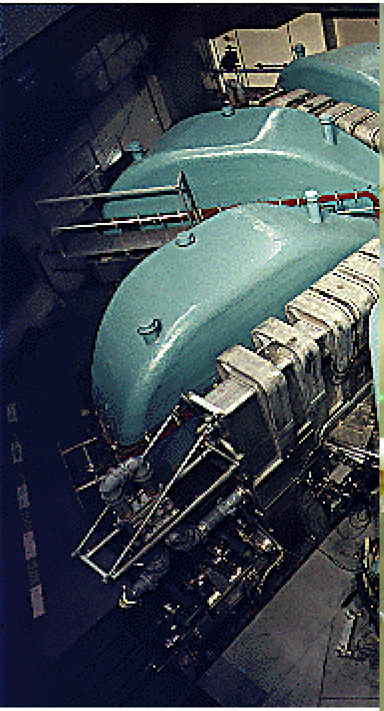
- beam trips
  - choice of machine architecture

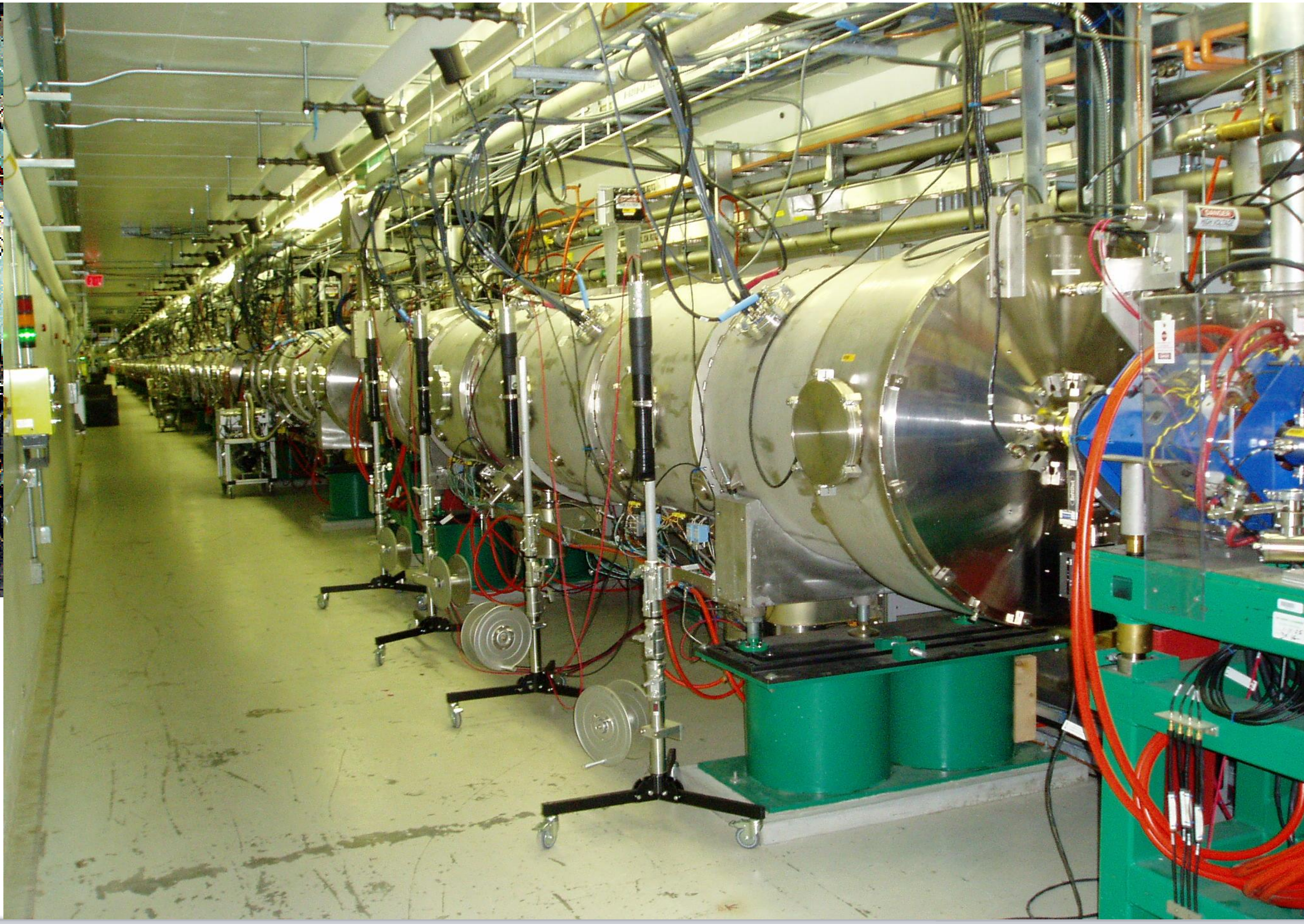
Initial challenges





Initial challenges



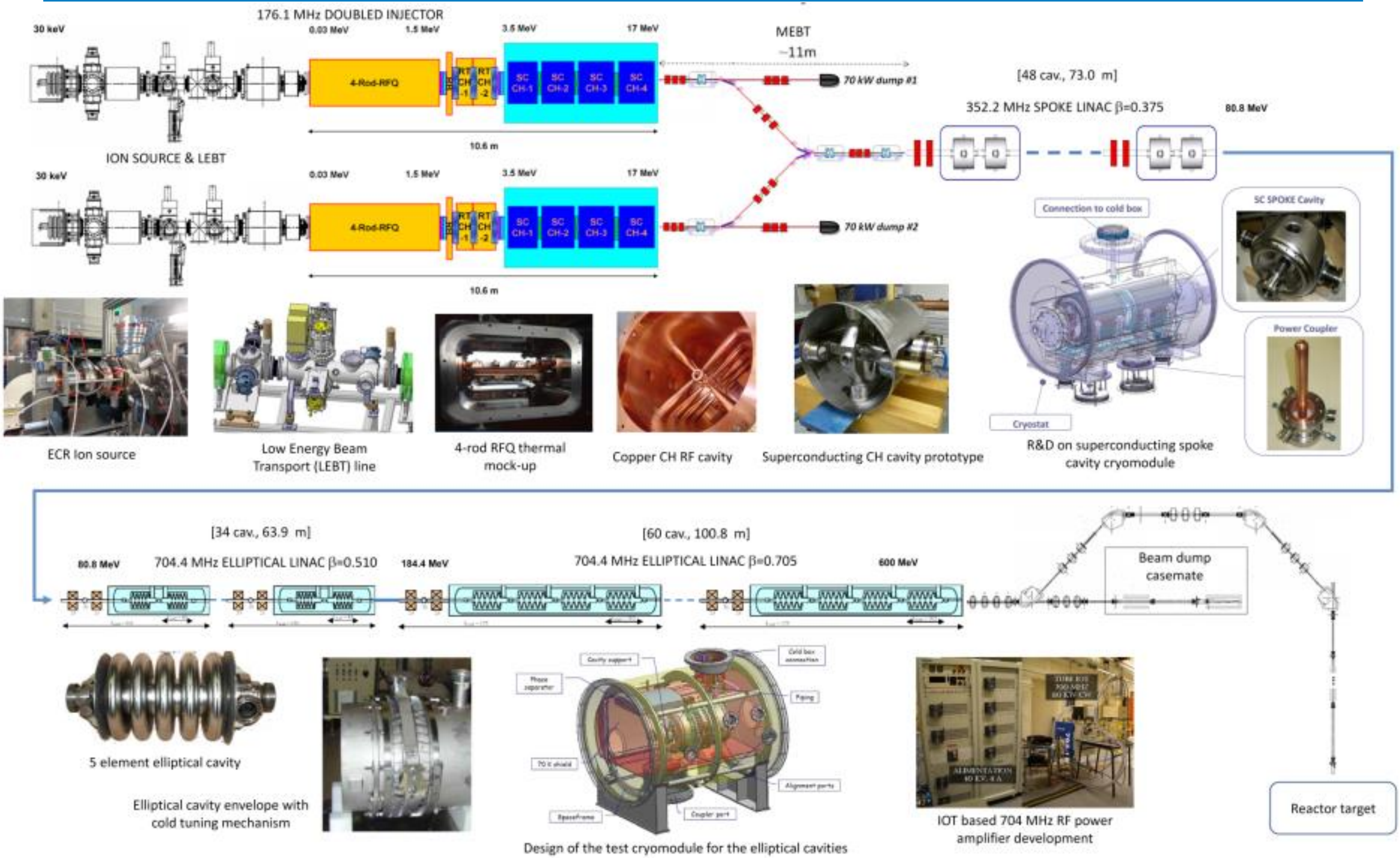


Initial challenges

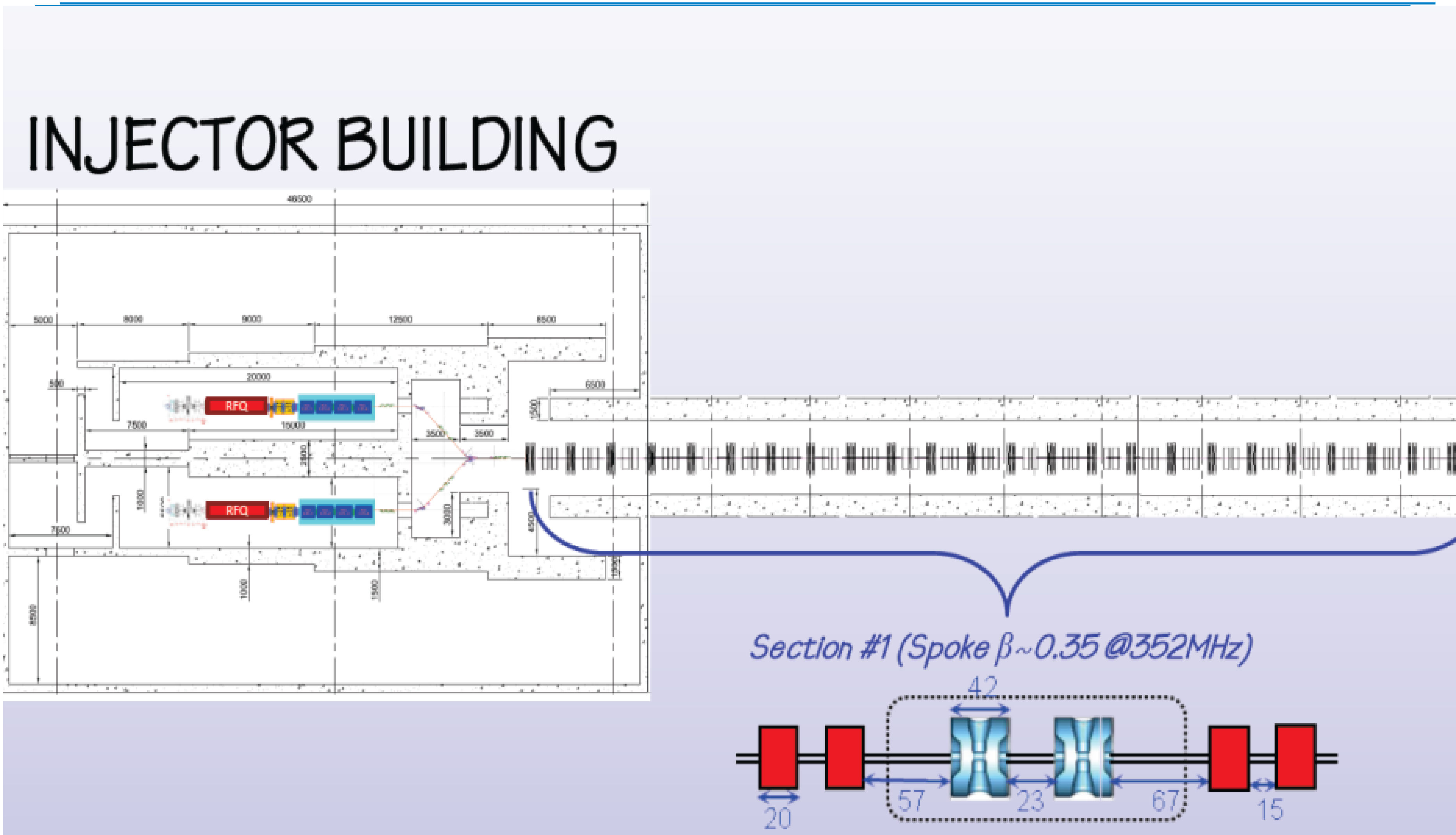
- organizational
  - SCK•CEN
  - European context
  - European Framework Programs: an opportunity !

- beam trips
  - choice of machine architecture → SC linac
  - exploit modularity → fault tolerance

MYRRHA Linear Accelerator: R&D fields



MYRRHA linac



1. path to mitigation

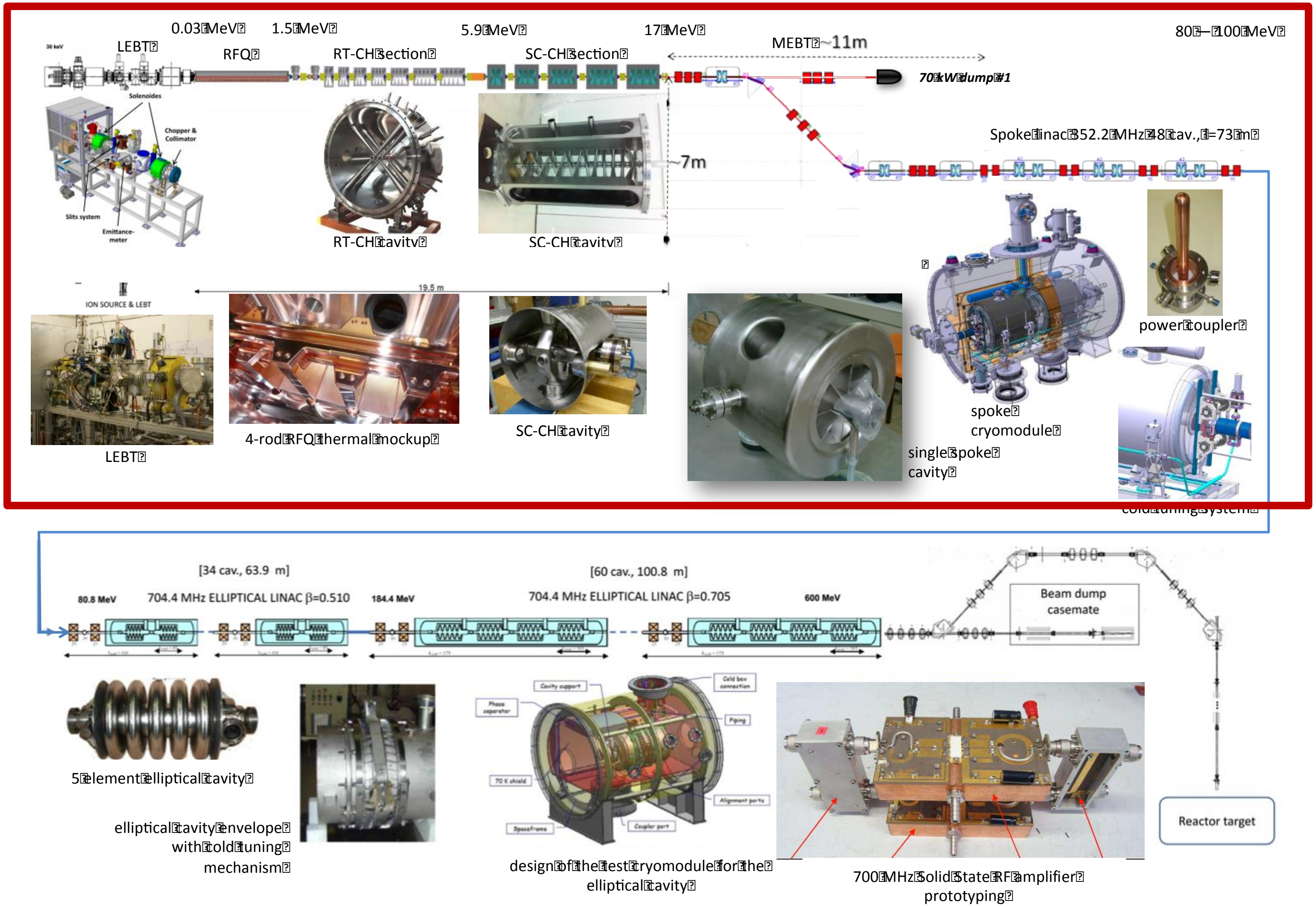
- engineering estimates
  - intrinsic MTBF at component level
    - → quality
    - → operational margins
  - fault tolerance at global level
    - → modularity
    - → redundancy
    - → operational margins

2. path to mitigation

- choice of (RF) technologies
  - RF superconductivity
    - → size reduction
    - → margins
  - Solid State RF amplifiers
    - → modularity
    - → industrial field, telecom driven
  - NC RF : unavoidable at low energy
    - → optimized cooling for CW operation

MYRRHA accelerator design

MYRRHA accelerator 0 – 100 MeV section

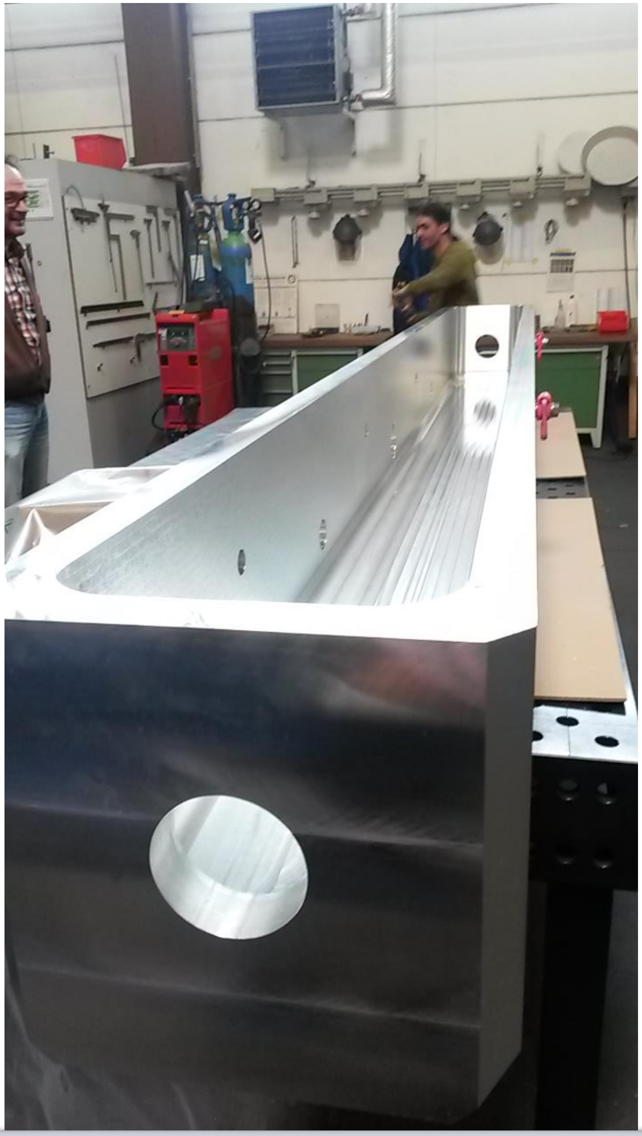


Prototyping 100 MeV

WP	R&D lots (APS act.)	MYRTE	env. partner	pres. status
IS	charact., ctrl. integr.		Pantechnik, SCK	OP
LEBT	chopper, SCC studies, PLC	*	LPSC, SCK	partly OP
RFQ	cavity, SSA, PLC	*	IAP, IBA, SCK	CONSTRUCT
CH sect.	optics, cav., magnets, SSA, diag., PLC		IAP, Industry, IBA	partly DESIGN
MEBT	optics, magnets, switch, rebunchers, dump, PLC		IPHC, LPSC, CERN	CONCEPT
Spoke	cryomodule, RF couplers, magnets, PLC	-	IPNO, LPSC, Industry	partly DESIGN
HEBT 100 MeV	optics, magnets, dump		IPHC, *CIEMAT*	0
Vacuum	layout, PLC		LPSC	0
Cryo	design, valve box		ACS, Industry, ?	CONCEPT
Diagnostics	global layout, BPM, BLM, FE electronics	-	CEA, IN2P3, Industry	initial CONCEPT
Controls	LLRF, timing, EPICS, virtual acc., GUI, user pgms, data bases, MPS	-	IPNO, Cosylab, CEA, Spiral2, SCK	CONCEPT, embryonic OP
Reliability	modeling, beam dynamics, tuning	-	EA, SCK, CEA, IN2P3	partly DESIGN
Integration	data base, 3D model, BOP		FEED, SCK, all	0
Test platform	installation, exploitation	-	SCK, all	mbryonic OP

IAP: 4-rod RFQ

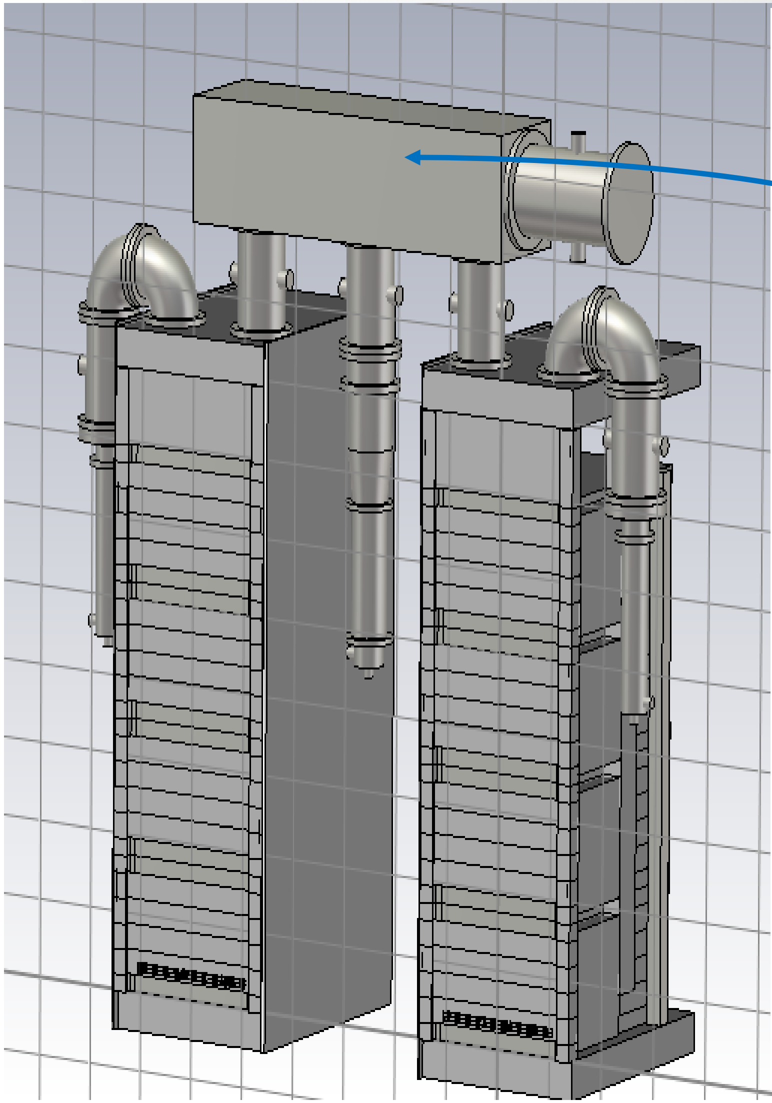
RFQ

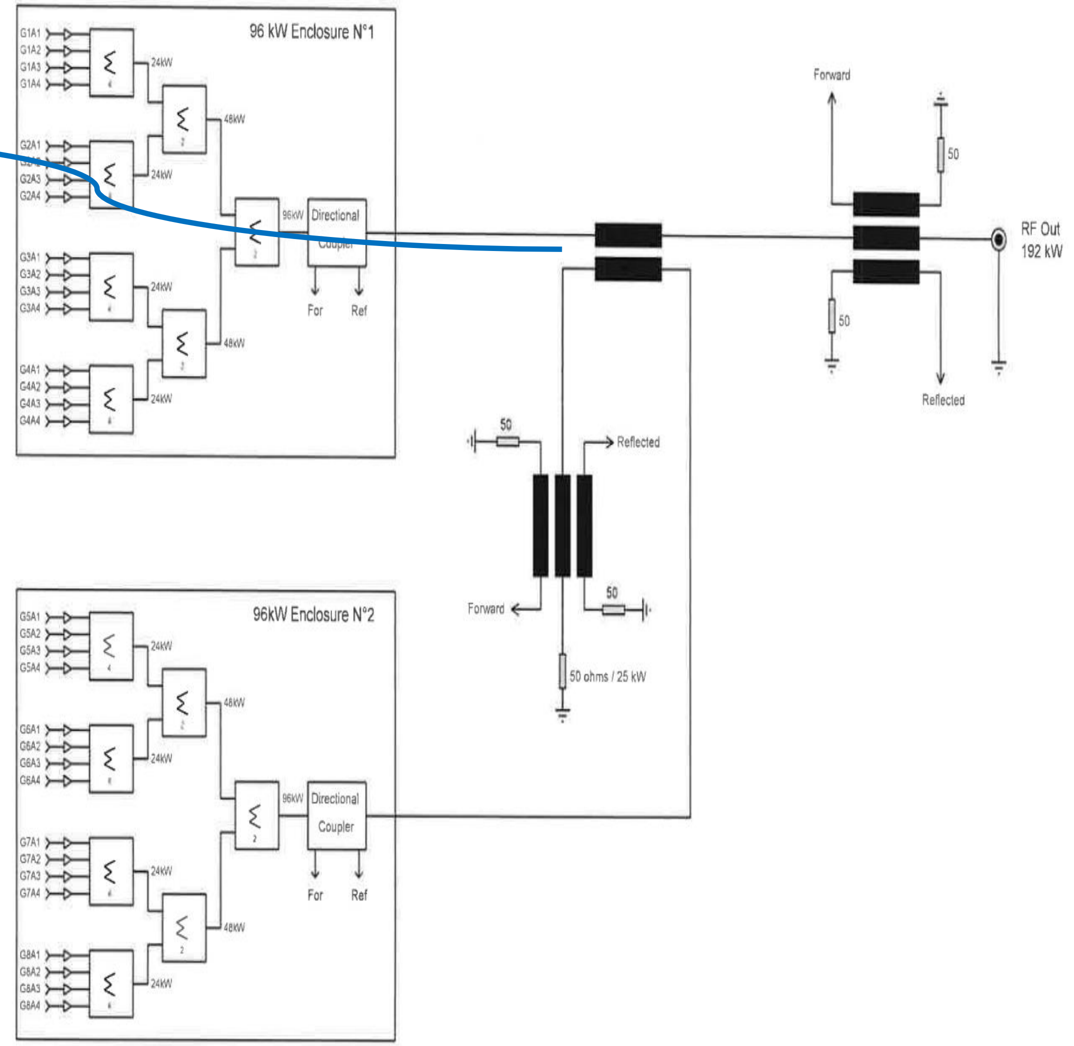


4 m long Aluminium RFQ tank machined at NTG

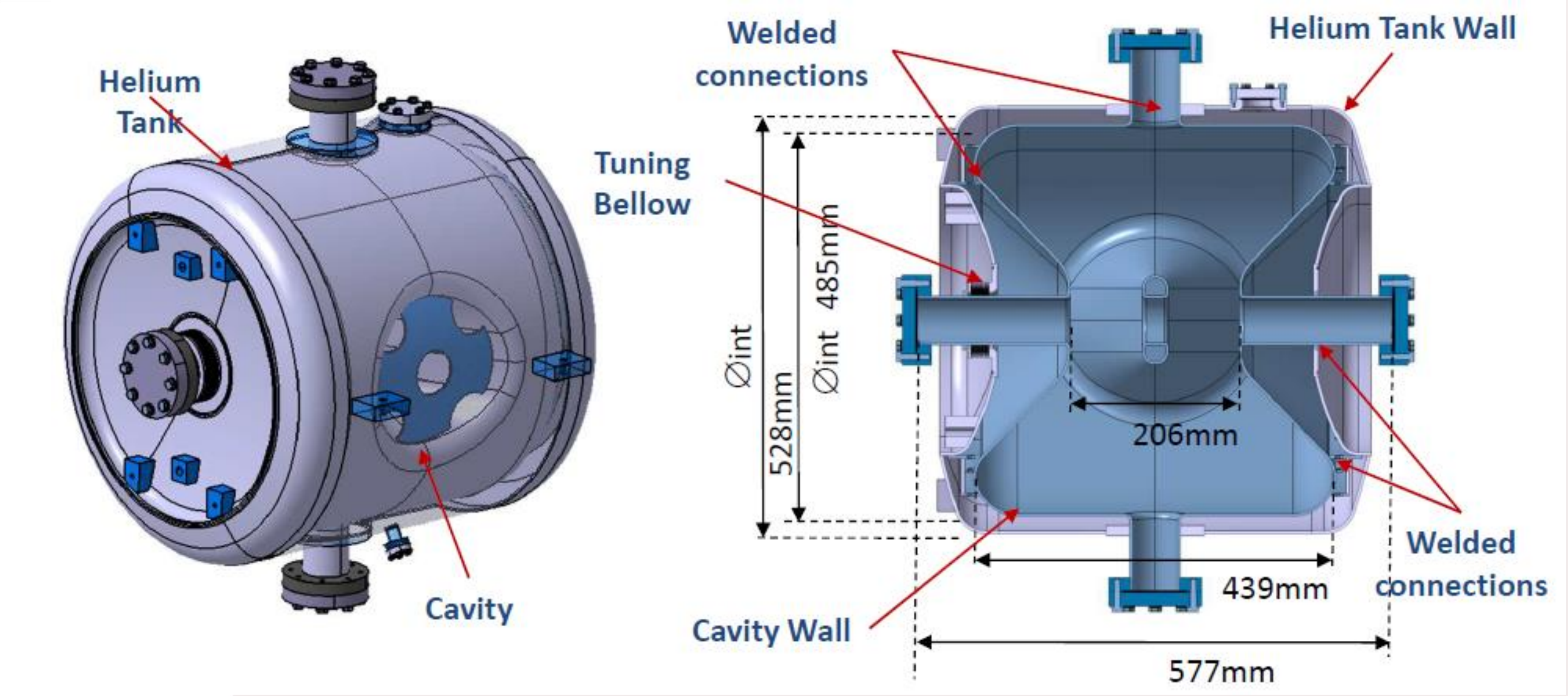
Courtesy of Michel Abs, IBA

Complete 160kW amplifier





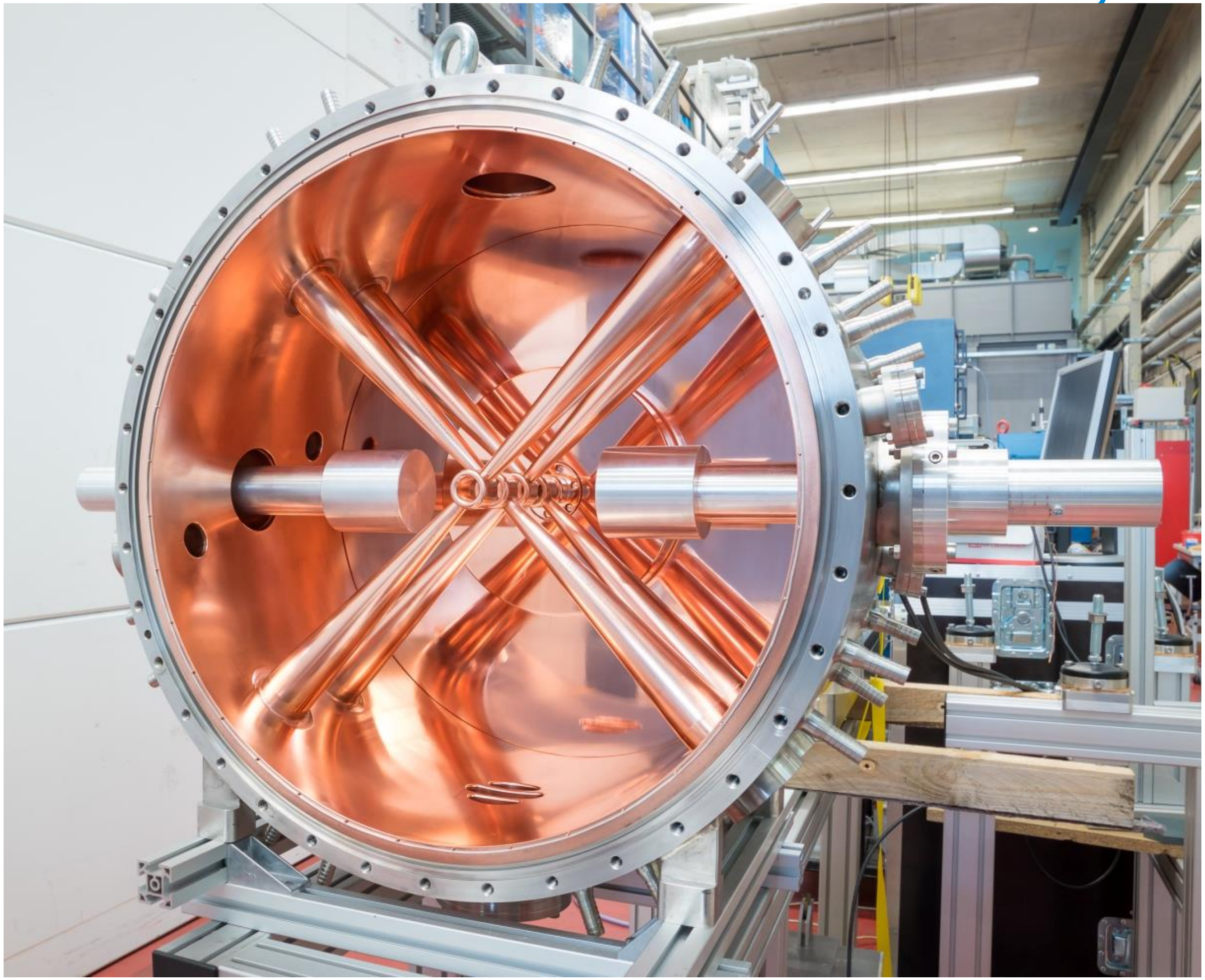
The MYRRHA spoke resonator : the design



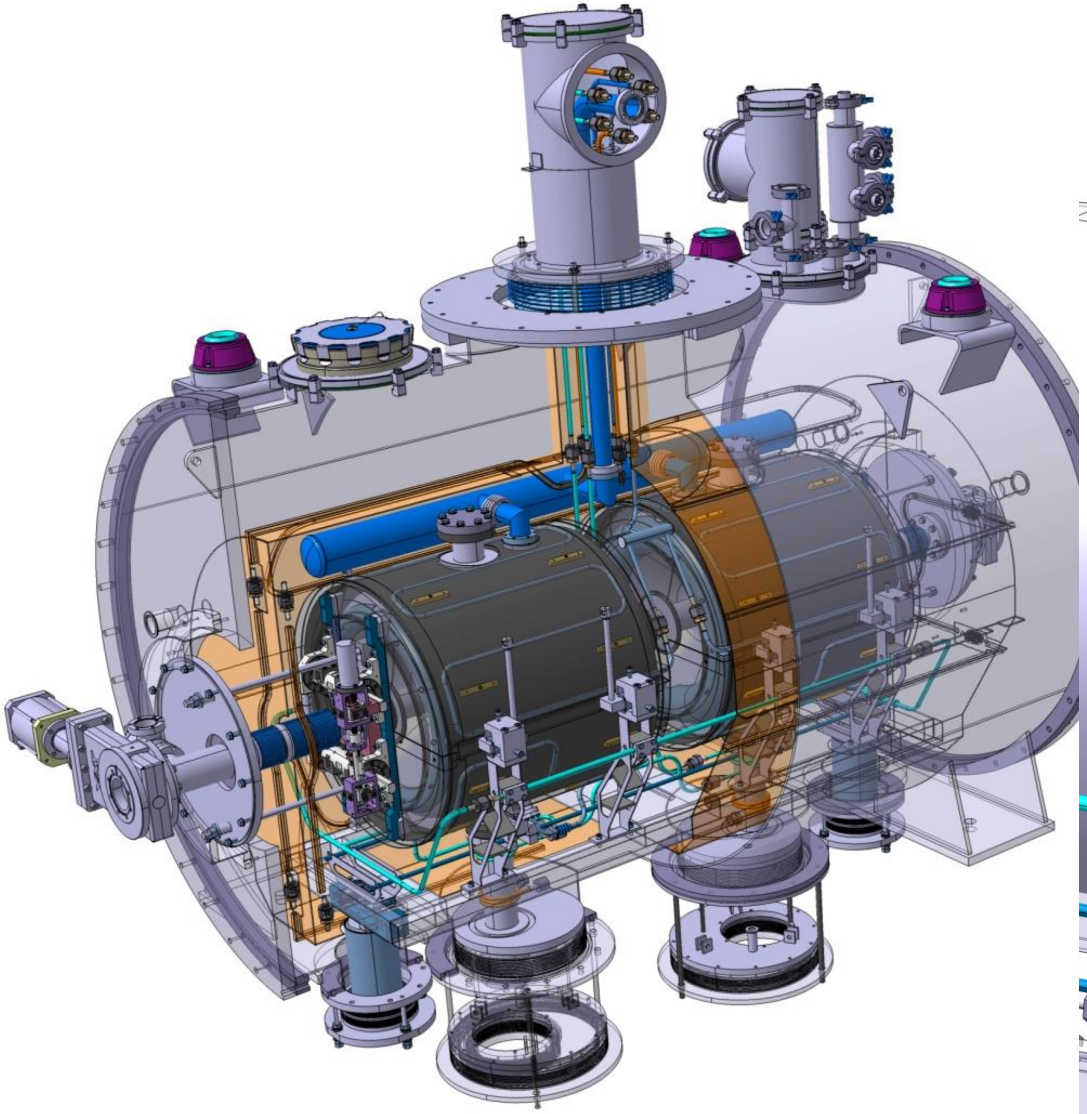
- 2 protypes designed during MAX project
- Built by Zanon and received the 1st december 2015

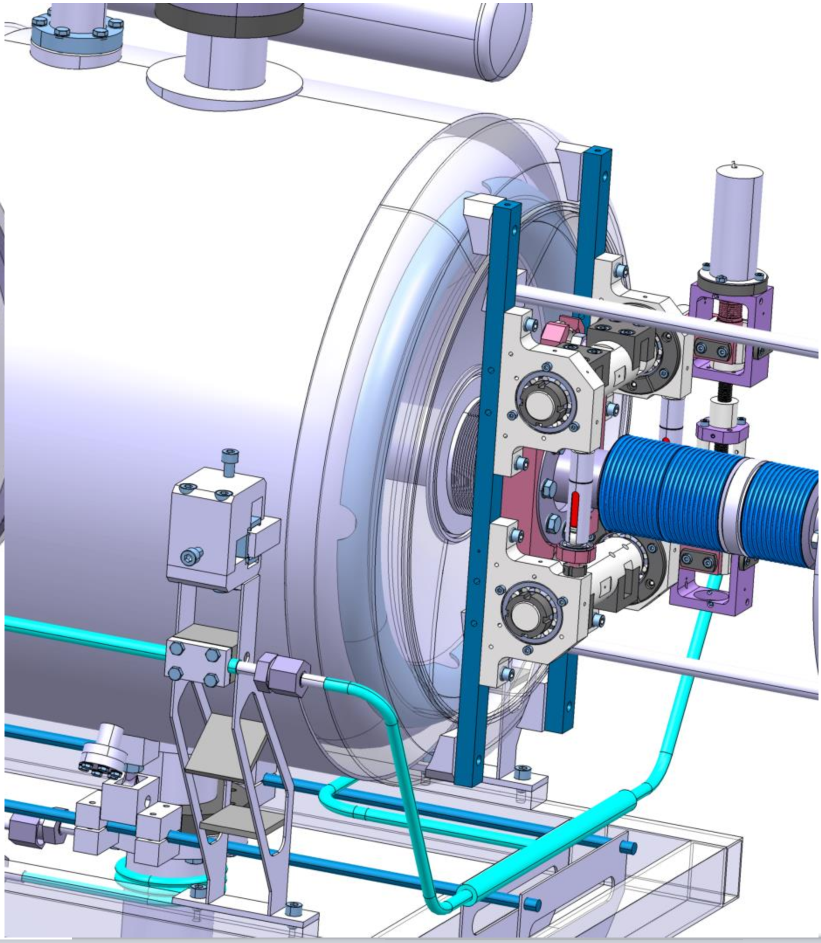
Courtesy of David Longuevergne, IPNO

IAP: CH cavity 175 MHz



Accelerator R&D





The MYRRHA spoke resonator : the delivery

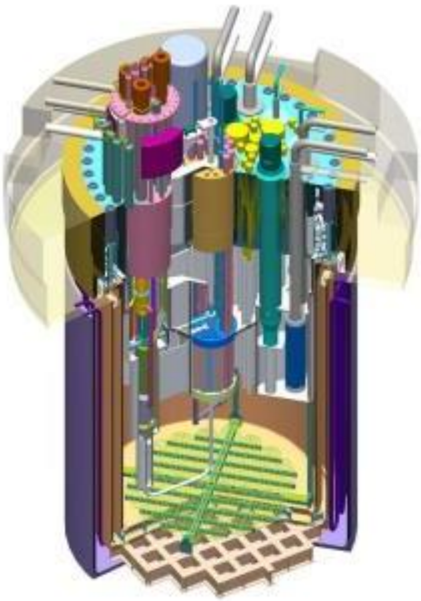
AMELIA
(ZA01)

VIRGINIA
(ZA02)

coupler test bench

- the MYRRHA single spoke cavities require RF power couplers capable of 40 kW CW
- the existing coupler design will be revisited
- it is foreseen to design and build a dedicated test bench
- need for a SS RF amplifier 80 kW 352 MHz

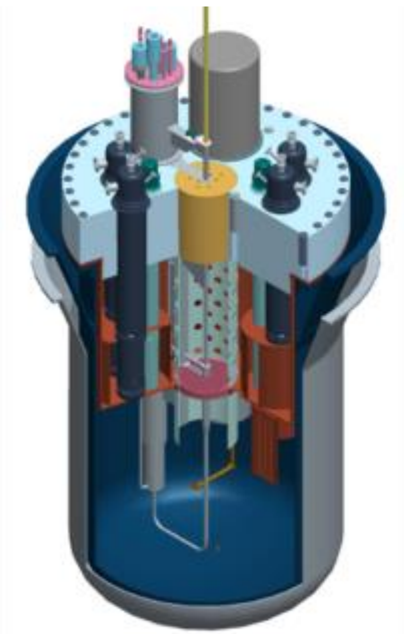
Evolution of MYRRHA reactor & spallation target design



Draft 2

2005

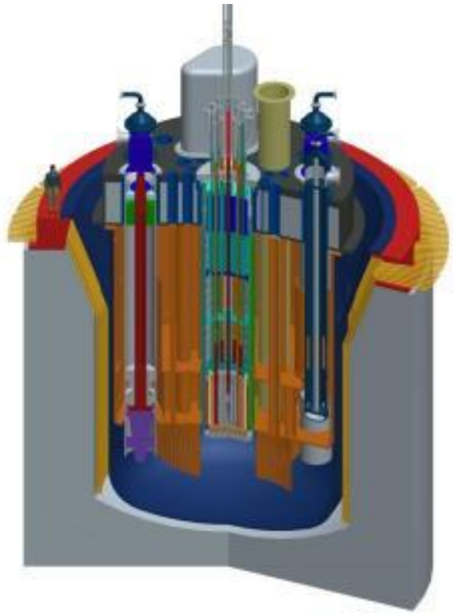
⇨



XT-ADS

2009

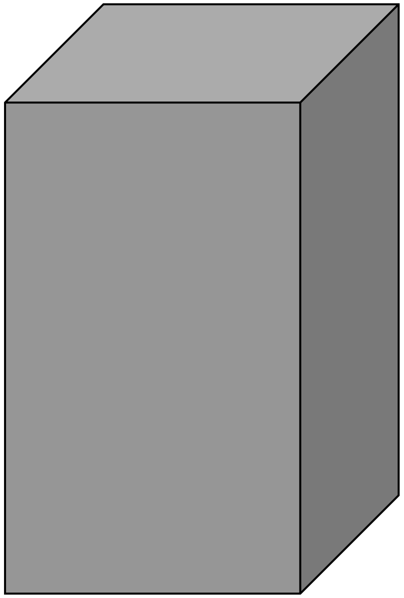
⇨



FASTEF

2012

⇨

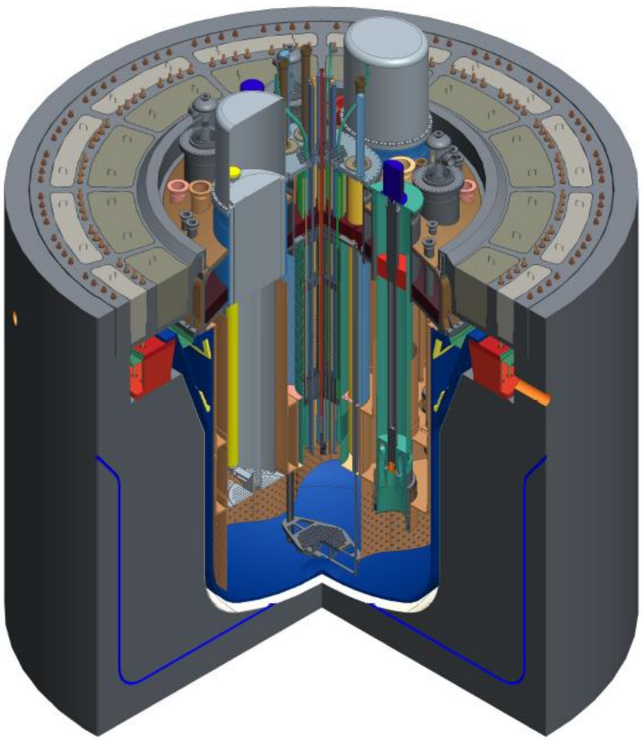


Rev. ?

2014

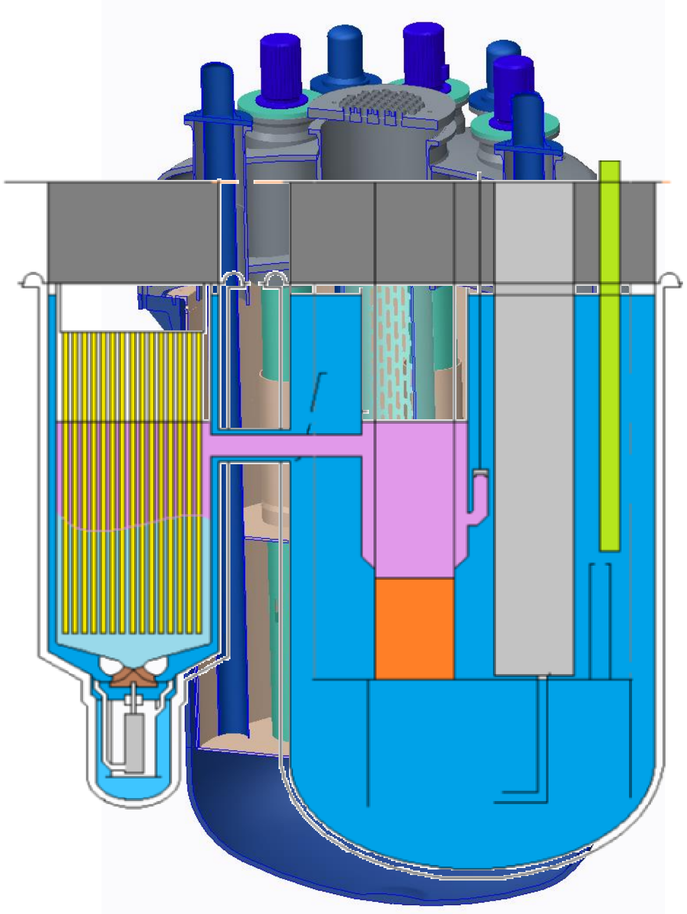
MYRRHA reactor design

- MYRRHA primary system rev. 1.6 consolidated
  - Operation in critical mode limited to 100 MW_{th}
  - Four lines of defence for major safety functions
- End 2014 total cost 1,6 G€
- Po-issue
- O_2-concentration control



MYRRHA design rev. 1.6
Ø reactor vessel : 10,4 m
Ø reactor skirt: 14,6m

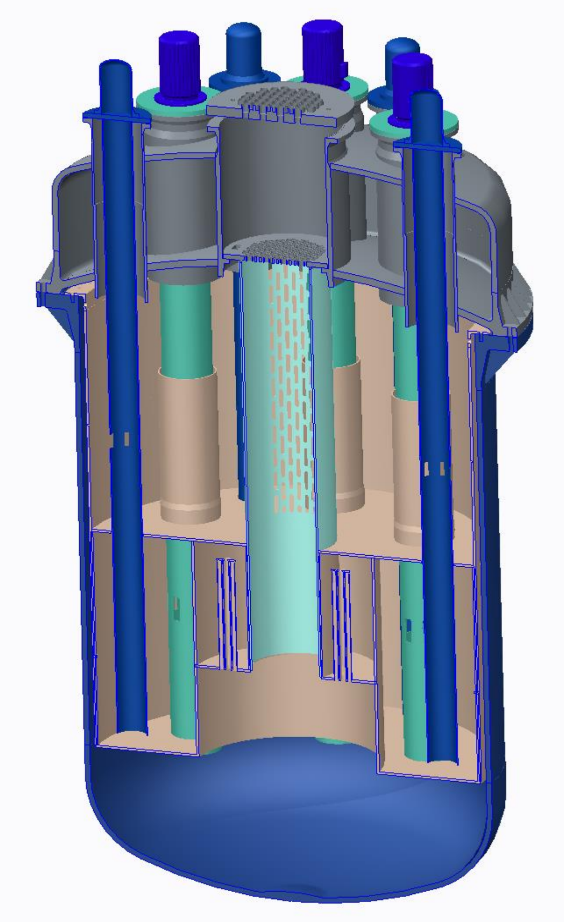
MYRRHA reactor design



- Four MYRRHA primary system design options investigated to reduce the dimension of the reactor vessel (& associated cost)

Option	Reactor type	Description
0	Pool	Updated rev. 1.6 Innovative IVFHM & double-walled PHX
1	Pool	Reduced size Innovative IVFHM & double-walled PHX
2	Loop	Bottom loading Existing IVFHM concept & external double-walled PHX
3	Loop	Top loading

MYRRHA reactor design



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2	Loop	Bottom loading Existing IVFHM concept & external double-walled PHX
3	Loop	Top loading

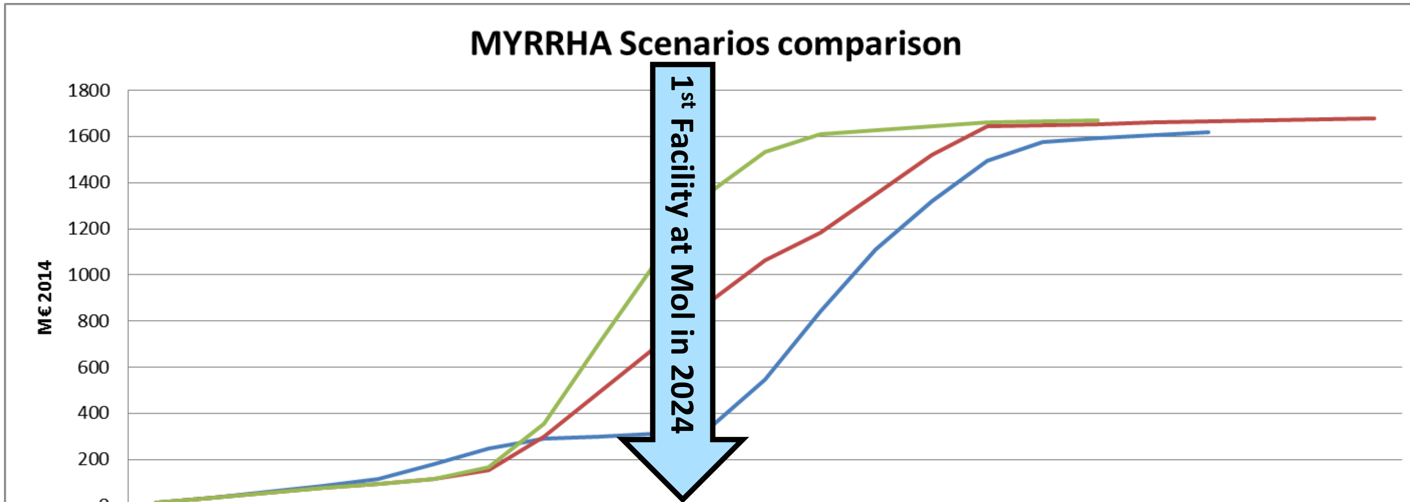
Option 0 is now the reference design under further optimisation

Implementation approach

- SCK•CEN investigated three scenarios for the implementation of MYRRHA:
  - SC1: Accelerator first + Reactor later
  - SC2: Reactor first + Accelerator later
  - SC3: Accelerator and Reactor all together
- Scenario one (SC1) was selected as the most appropriate approach for the realisation of MYRRHA
  - Reducing the technical risks
  - Spreading the investment cost
  - Allowing first R&D facility available by 2024

Financing scheme
> Scenario 1

- Spreads investment cost with smaller upfront investment value
- Mitigates risk related to accelerator reliability and allows more time for risk reduction on the reactor
- Extends timeline
  - For solving innovative reactor design options
  - For building & extending consortium
- **Allows new facility by 2024 at SCK•CEN**



	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
SC1	11,3	34,5	59,3	83,8	115,3	177,7	249,3	288,8	298,3	311,8	339,3	547,5	841,3	1113	1320	1497	1577	1592	1607	1619			
SC2	11,3	33,3	56,3	79,3	96,3	116,8	153,9	300,9	493,5	683	882,7	1066	1182	1350	1519	1643	1650	1655	1661	1667	1672	1676	1679
SC3	11,3	33,3	56,3	79,3	96,3	116,8	166,9	355,4	703,5	1049	1359	1533	1611	1628	1645	1661	1666	1669					

Implementation approach
Phase 2 & 3: sequential or in parallel

2024: Stage-gate decision

Phase 1

LINAC injector & accelerator & exp. Stations up to 100 MeV

Preparations

Preparing the construction of SPs 2 & 3

Phase 2

Upgrade to 600 MeV

Phase 3

Reactor & spallation target module

Phase 1

LINAC injector & accelerator & exp. Stations up to 100 MeV

Phase 2

Upgrade to 600 MeV

Preparations

Preparing the construction of SP 2 & 3

Phase 3

Reactor & spallation target module

Global planning

Phase 1
LINAC Injector + Accelerator + experimental stations up to 100 MeV

2016	2017	2018	2019	2020	2021	2022	2023	2024

Phase 1: 100 MeV Accelerator built and commissioned in 2024

WP 1.1 - 100 MeV Accelerator R&D, design and construction

Phase 2: 600 MeV Accelerator preparatory phase - establish basis for decision on construction

WP 1.2 - 100 MeV Accelerator Balance of Plant

WP 2.1 - 600 MeV Accelerator R&D, design for taking decision in 2025

Phase 3: MYRRHA reactor preparatory phase - establish basis for decision on construction in 2025

WP 2.2 - 600 MeV Accelerator Balance of Plant

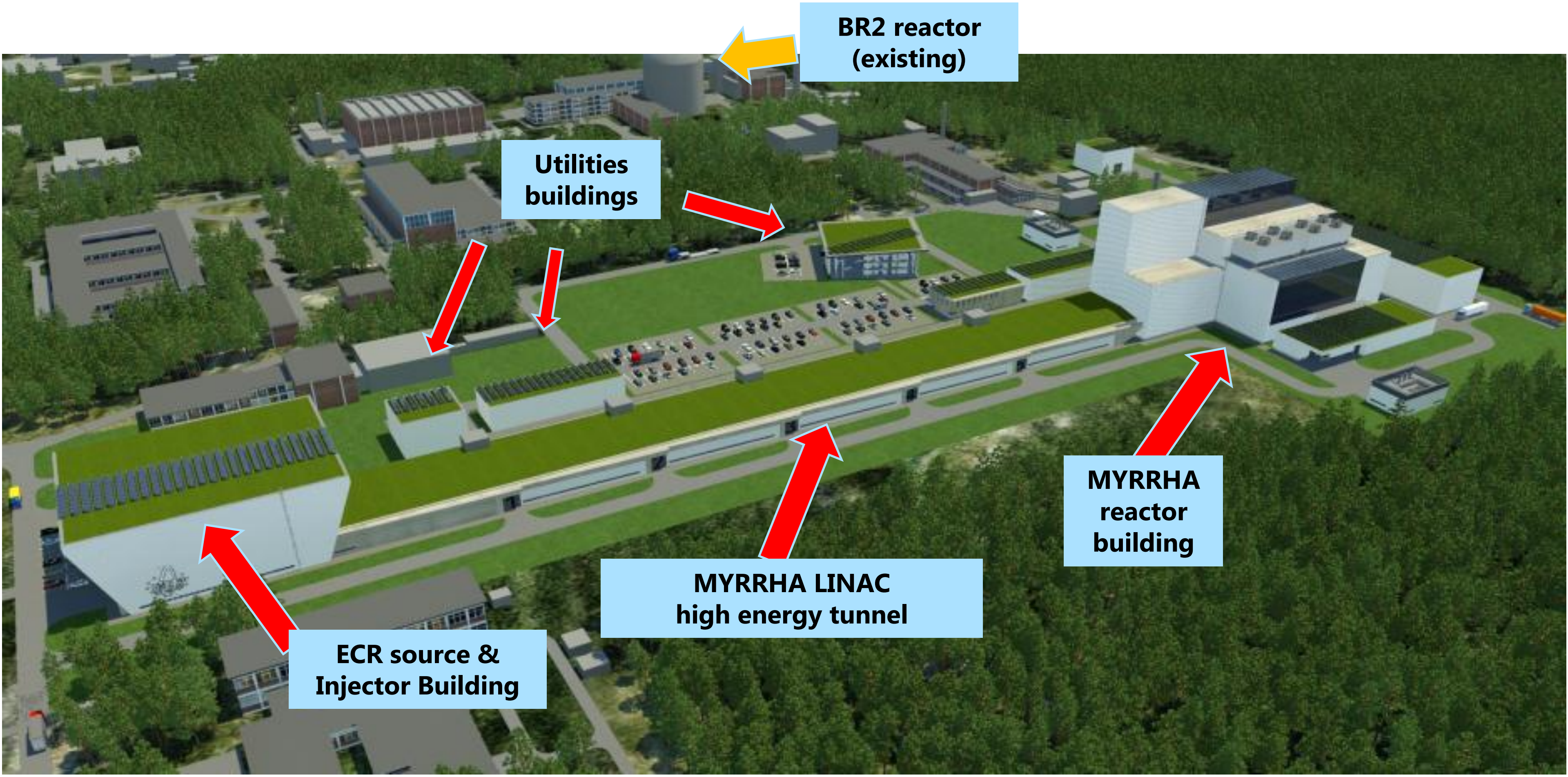
WP 3.1 – Primary System Design

WP 3.2 – Primary System R&D Supporting Programme

WP 3.3 – Balance Of Plant Primary System

With a positive decision in 2017, we will break ground in 2020

MYRRHA fully developed as:
An international, innovative and unique facility at Mol (BE)



SCK•CEN
Studiecentrum voor Kernenergie
Centre d'Etude de l'Energie Nucléaire
Belgian Nuclear Research Centre

Stichting van Openbaar Nut
Fondation d'Utilité Publique
Foundation of Public Utility

Registered Office: Avenue Herrmann-Debrouxlaan 40 – BE-1160 BRUSSELS
Operational Office: Boeretang 200 – BE-2400 MOL

STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE