Accelerator Driven Systems (ADS)

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Joint Universities Accelerator School

Archamps, France

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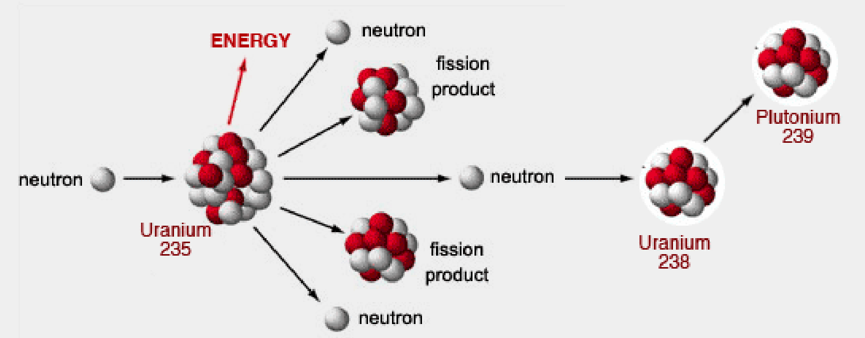
Overview

1. INTRODUCTION

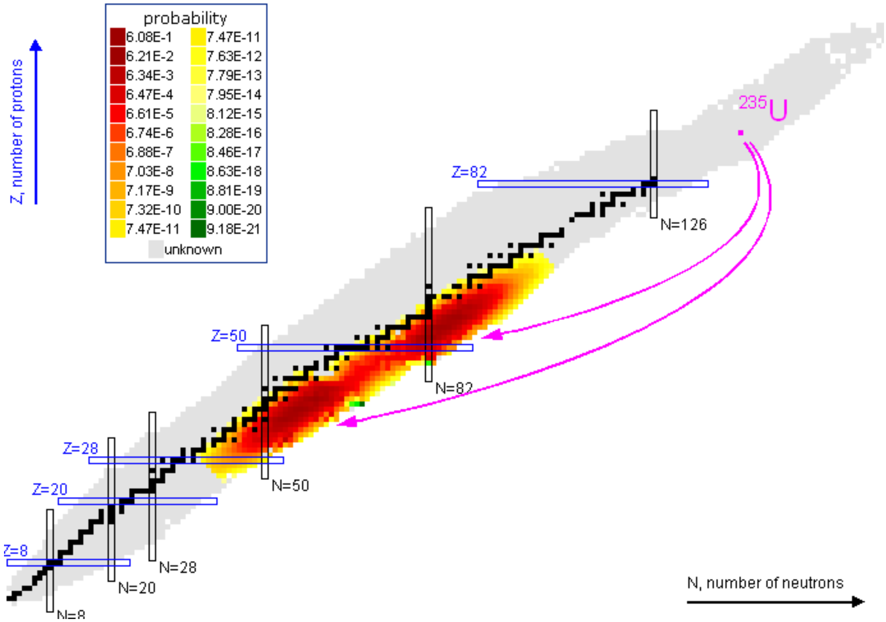
- Nuclear waste
- Partitioning & transmutation (P&T)
- ADS concept

Formation of nuclear waste

- Nuclear cycle generates

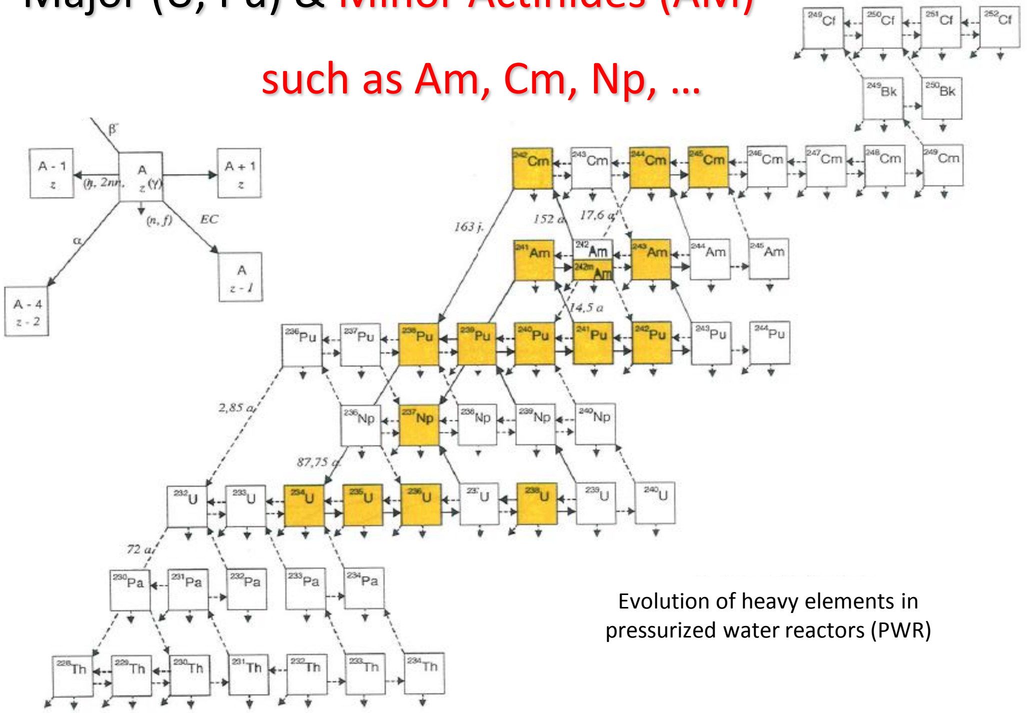


- Fission Products



- Major (U, Pu) & Minor Actinides (AM)

  such as Am, Cm, Np, …



Evolution of heavy elements in pressurized water reactors (PWR)

Nuclear waste : present situation

- About 2500 tons of Spent Nuclear Fuel are produced every year by 145 reactors in Europe

- High Level Waste (HLW)

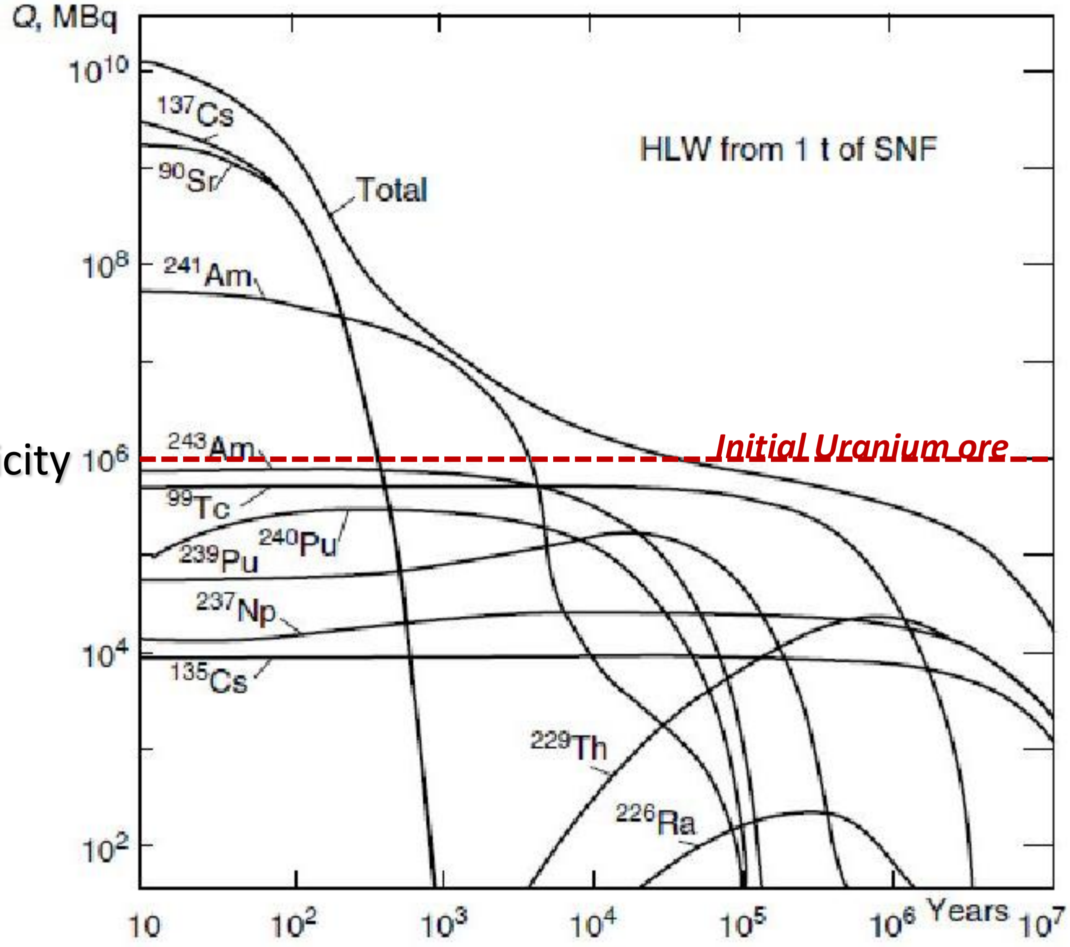
  - represent 0.2% in volume & 95% in radiotoxicity

  - long-term dominated by **Minor Actinides** (especially ^{241}Am)

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

  - CIGEO project (France)

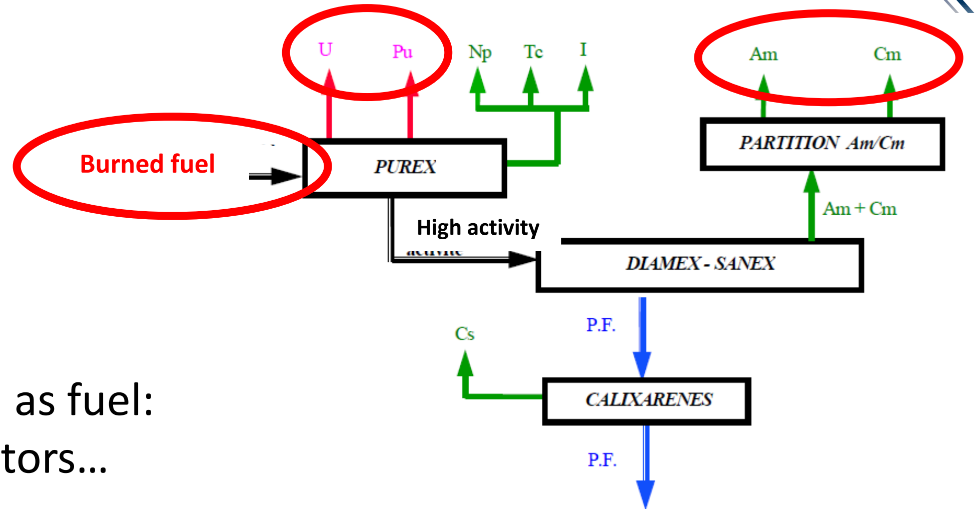
  - Yucca mountain (USA, defunded in 2011)



Activity of High Level Waste remaining after processing of 1 ton of Spent Nuclear Fuel as a function of time

Spent fuel reprocessing (partitioning)

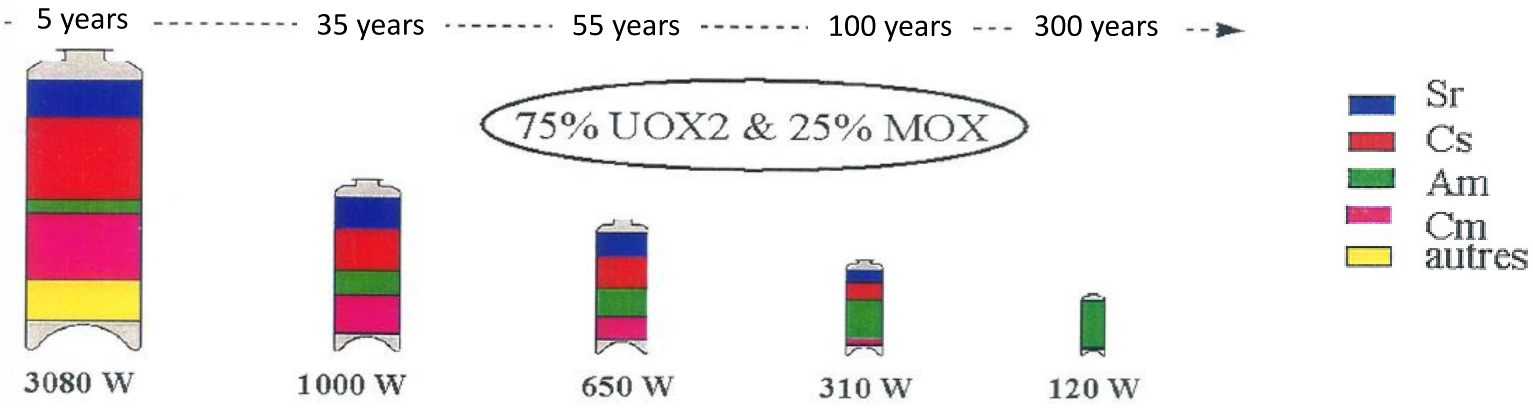
- In France (La Hague), **spent fuel is reprocessed**



- U and Pu are extracted (partitionning) to be reused as fuel: Mixed OXide fuel (MOX), future Gen.IV reactors…

- High-level wastes are conditionned (vitrification) & stored

Vitrified container



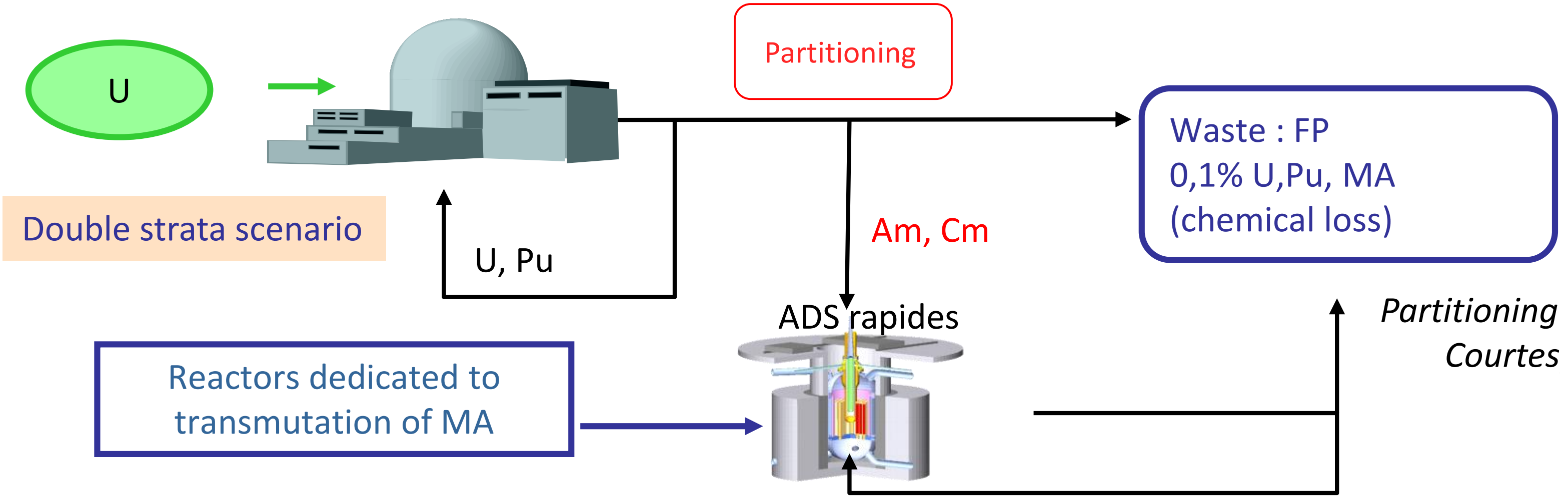
Transmutation with ADS

- Instead of storing the long-lived waste, **the transmutation strategy proposes to:**

  reduce radiotoxicity and heat loads of long-lived nuclear wastes (especially MA)

  to minimize the surface required for waste storage

- **ADS** = present reference solution for dedicated "transmuter" facilities
- Possible scenario with 2 types of reactor (double-strata)
  - Classical reactor for energy production
  - ADS for minor actinides management (not competitive for electricity production)
- A "small" 400 MW_{th} industrial ADS could burn 100 kg of MA/year (about 20 units for EU)



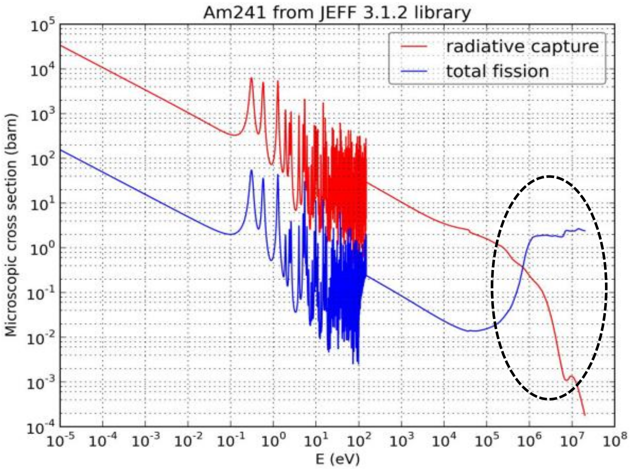
Partitioning & transmutation scenario
Courtesy S. David (CNRS)

Present options for transmutation of minor actinides

Transmutation of minor actinides (MA) into fission products is efficient only if:

- ➢ Fission to capture cross section ratio is high enough
- ➔ **Need for a fast neutron spectrum (MeV)**
- ➢ Enough neutrons are available to feed the transmutation process
- ➔ **Need for an intense neutron source**

Am241 cross section



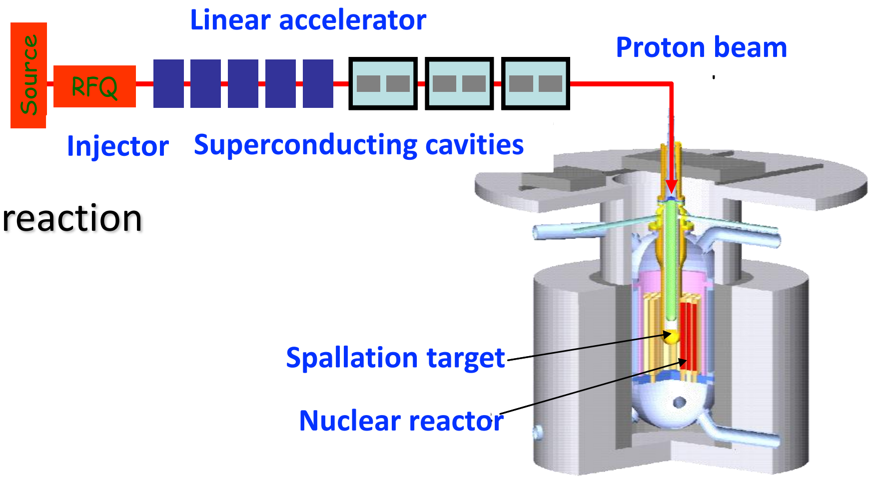
In which type of fast reactor could we transmute ?

- ➢ In the next generation GEN-IV nuclear power plants (critical Fast Reactors)
  - ➢ only a small fraction of MA can be loaded
- ➢ In a few **dedicated MA burners** (ADS)
  - ➢ highly loaded with MA : higher efficiency

➔ sensitive compromise between **safety / economics / proliferation / politics…**

Introduction to Accelerator Driven System

- Accelerator Driven System (ADS) :
  - nuclear facility envisioned in waste management programs



- Based on a sub-critical reactor
  - Requires a external neutron source to maintain the chain reaction
  - External source = accelerator + target
  - Reactor driven by the source via the accelerator beam

- Allow a fuel with large amounts of minor actinides to be incinerated
  - impossible in critical reactors

ADS {
Reactor
Accelerator ➔ this talk
Target

Basic concepts of ADS

- A subcritical system driven by an external source of neutrons to operate
  - Spallation neutrons produced by an proton beam on target

- ADS reactor specificities
  - Subcritical : neutron multiplication factor $k_{eff} < 1$ (typically between 0.93 & 0.97)
  - Minimal probability of runaway reaction : reactor inherently safe
  - Some very fast neutrons (> 20 MeV) in the core
  - The beam pipe may break containment barriers

- First approximation :
  - Thermal Power of depends on the spallation target and the proton beam properties

P_{th}: Thermal power of the reactor
E_f : Energy generated per fission ($\sim$200 MeV)
ν : Neutrons emitted per fission ($\sim$2.5)
I : Proton beam current
k_{eff} : Effective neutron multiplication factor
φ^*: Source importance ($\sim$1.5) – characterise the efficiency of the external neutrons and thus the coupling quality (Source/Reactor).
ζ_{spal} : Spallation target neutron yield per incident proton ($\sim$30, for a 1 GeV proton on LBE target)

$$P_{th}(MW_{th}) = E_f\,(MeV).I(A).\frac{\varphi^*.k_{eff}}{1-k_{eff}}.\frac{\zeta_{spal}}{\nu}$$

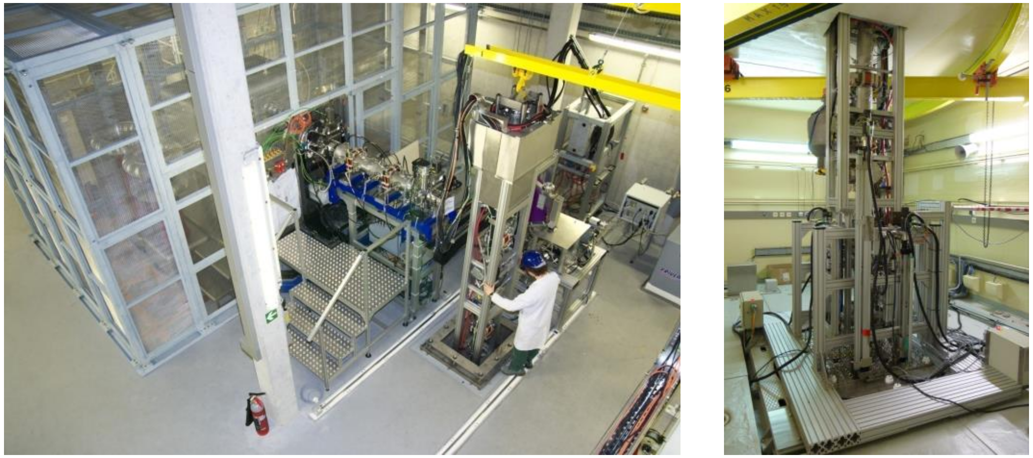
ADS demonstrator (multi-MW$_{th}$) ➔ Need for a multi-MW proton beam

2. EXAMPLE OF A LOW POWER ADS :

- THE GUINEVERE MOCK-UP

Towards high power ADS

- On the path to power ADS based on multi-MW reactor and multi-MW beam, several experiments
  - CERN, C. Rubbia *et al.* (CERN, 1995-1996)
    - Experiments FEAT (Fast Energy Amplifier Test) & TARC (Transmutation by Adiabatic Resonance Crossing)
  - MUSE, Cadarache, France, 2000-2004 (CEA, CNRS) low-power coupling of
    - d electrostatic accelerator + tritium target (dT) + MASURCA reactor
  - KUCA, Japan since 2009
    - FFAG (100 MeV protons, nA) on tungstene target, or dT accelerator + Kyoto University Critical Assembly
  - GUINEVERE in Belgium (CNRS, SCK-CEN) since 2011 : low-power coupling of
    - d electrostatic accelerator + tritium target (dT) + fast lead core



*Guinevere at SCK*CEN (Belgium), operated since 2011*

GUINEVERE mock-up (CNRS, F & SCK-CEN, Be)

GUINEVERE : Generator of Uninterrupted Intense NEutrons
at the lead VEnus Reactor (Mol, Belgium)

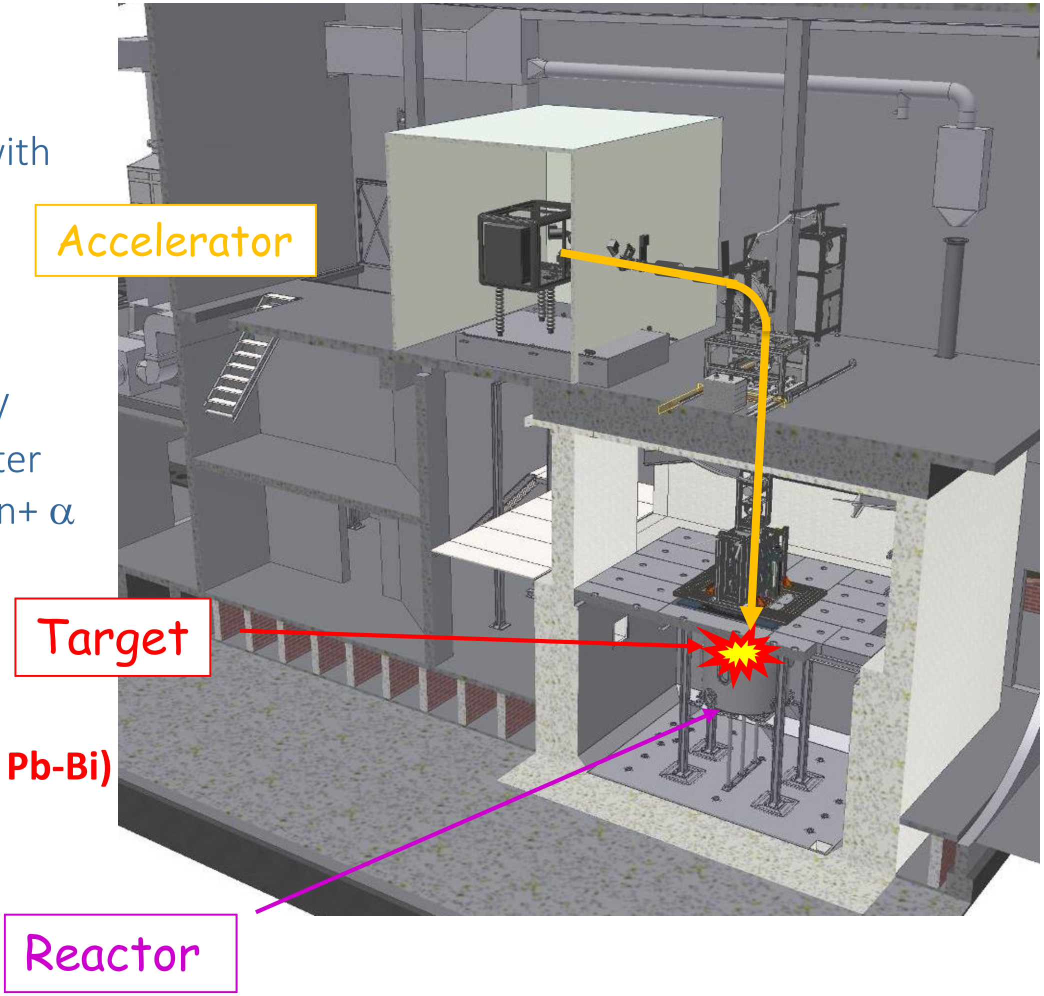
- **VENUS-F** : low-power (100 W) sub-critical fast reactor with enriched U, with solid Pb-Bi « coolant »

+

- **GENEPI-3C** : electrostatic accelerator producing 220-keV deuterons (250 W) on a **tritium target** located at core center to generate 14-MeV neutrons by fusion reaction T+ D ➔ n+ α

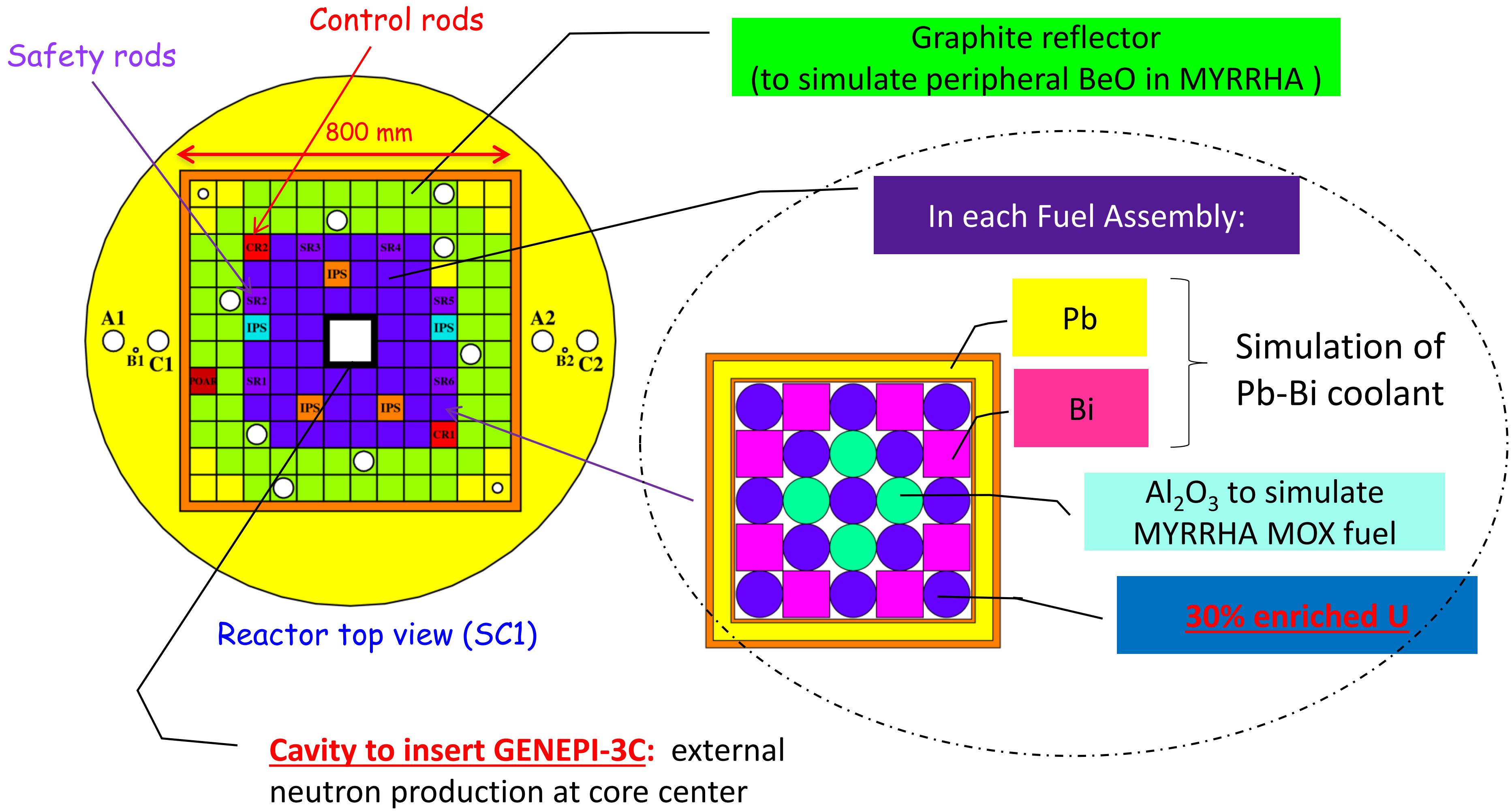
=

A « mock-up » of the power ADS MYRRHA (cooled with Pb-Bi)



GUINEVERE mock-up : MYRRHA-like core

- Reactor configuration SC11 : as representative as possible of MYRRHA with $k_{eff} = 0.95845 < 1$



Safety rods

Control rods

Graphite reflector
(to simulate peripheral BeO in MYRRHA)

In each Fuel Assembly:

Pb

Bi

Simulation of Pb-Bi coolant

Al_2O_3 to simulate MYRRHA MOX fuel

30% enriched U

Reactor top view (SC1)

Cavity to insert GENEPI-3C: external neutron production at core center

JL Lecouey, MYRTE final meeting, February 2019

GUINEVERE mock-up : reactivity monitoring method

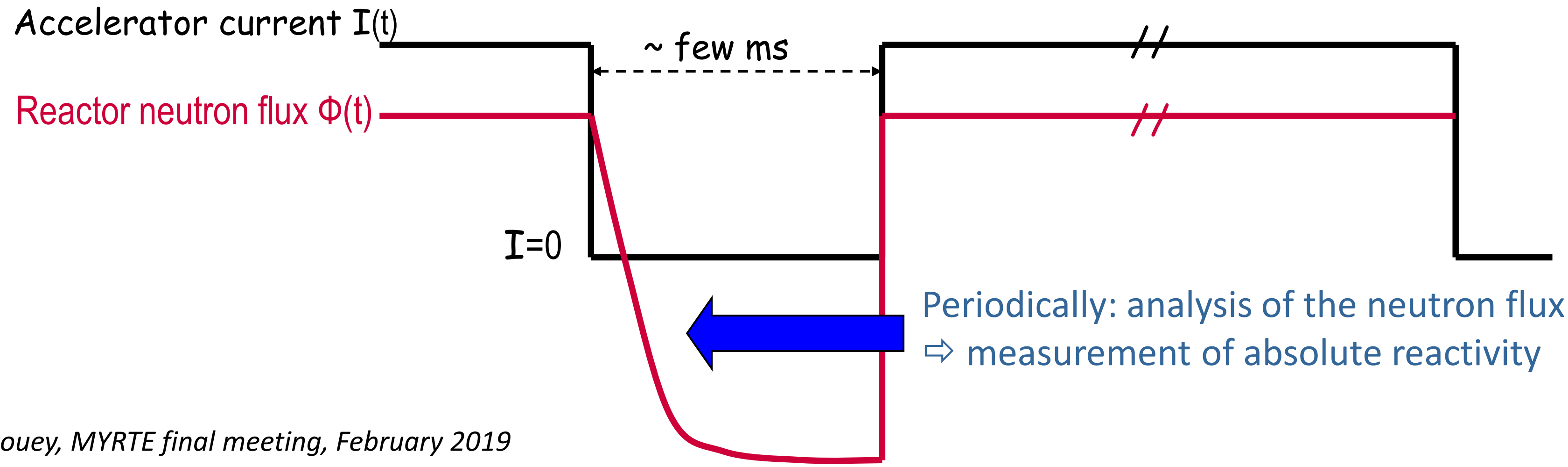
- Reactivity monitoring

A reactor key parameter : Reactivity : $\rho = \frac{k_{\text{eff}} - 1}{k_{\text{eff}}}$

Subcriticality (negative reactivity) of the reactor must be checked during ADS operation

ρ	Reactor	Power
> 0	Supercritical	Self-Increase
= 0	Critical	Self-sustained
< 0	**Subcritical**	**Accelerator Driven**

- Special beam mode required to measure the reactivity
  ➔ The accelerator produces alternatively
  - Continuous mode to mimic a high power ADS operation (MYRRHA)
  - Interrupted continous mode to allow reactivity measurements

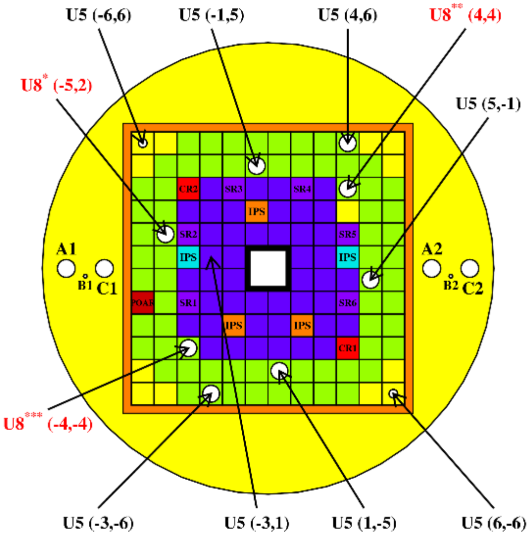


Periodically: analysis of the neutron flux decay curve
⇨ measurement of absolute reactivity

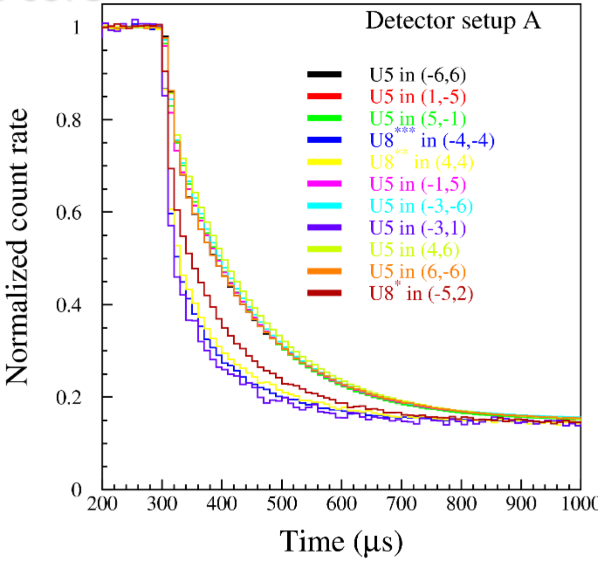
JL Lecouey, MYRTE final meeting, February 2019

GUINEVERE mock-up : reactivity monitoring results

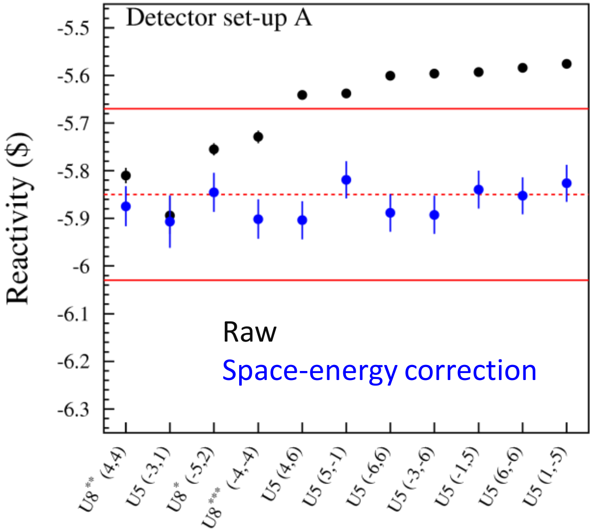
- Neutron detectors (fission chambers) at different locations in the core



Beam interruption



- Monitoring of core reactivity :
  - excellent agreement bewteen 2 techniques
    - the reference technique (Modified Source Multiplication)
    - the beam interruption analysis method
  - Fine corrections must be applied



➔ **beam interruptions allow reactivity monitoring**

JL Lecouey, MYRTE final meeting, February 2019

GUINEVERE mock-up : operational feedback

- Beam loss, often created by severe discharges, can affect the reactor
  - After a discharge, beam can be lost on target
  - Neutron production in reactor drops within tens of µs
  - During long interruptions (~s) reactor monitors detect a drop in neutron counts
  - When beam is restored, the monitors detect a sudden increase of neutron rate
  - If neutron multiplication rate exceeds reactor safety limit

    ➔ Trigger of reactor emergency shutdown (SCRAM)

    ➔ All reactor rods drop (safety and control rods)

- Reactor startup required to recover from every SCRAM requires ~30 minutes
  - Rod liftup sequence: 6 safety rods one by one, then 2 control rods simultaneously

- Reactor SCRAMs : major cause of facility downtime

➔ **machine reliability is the key to operate an ADS**

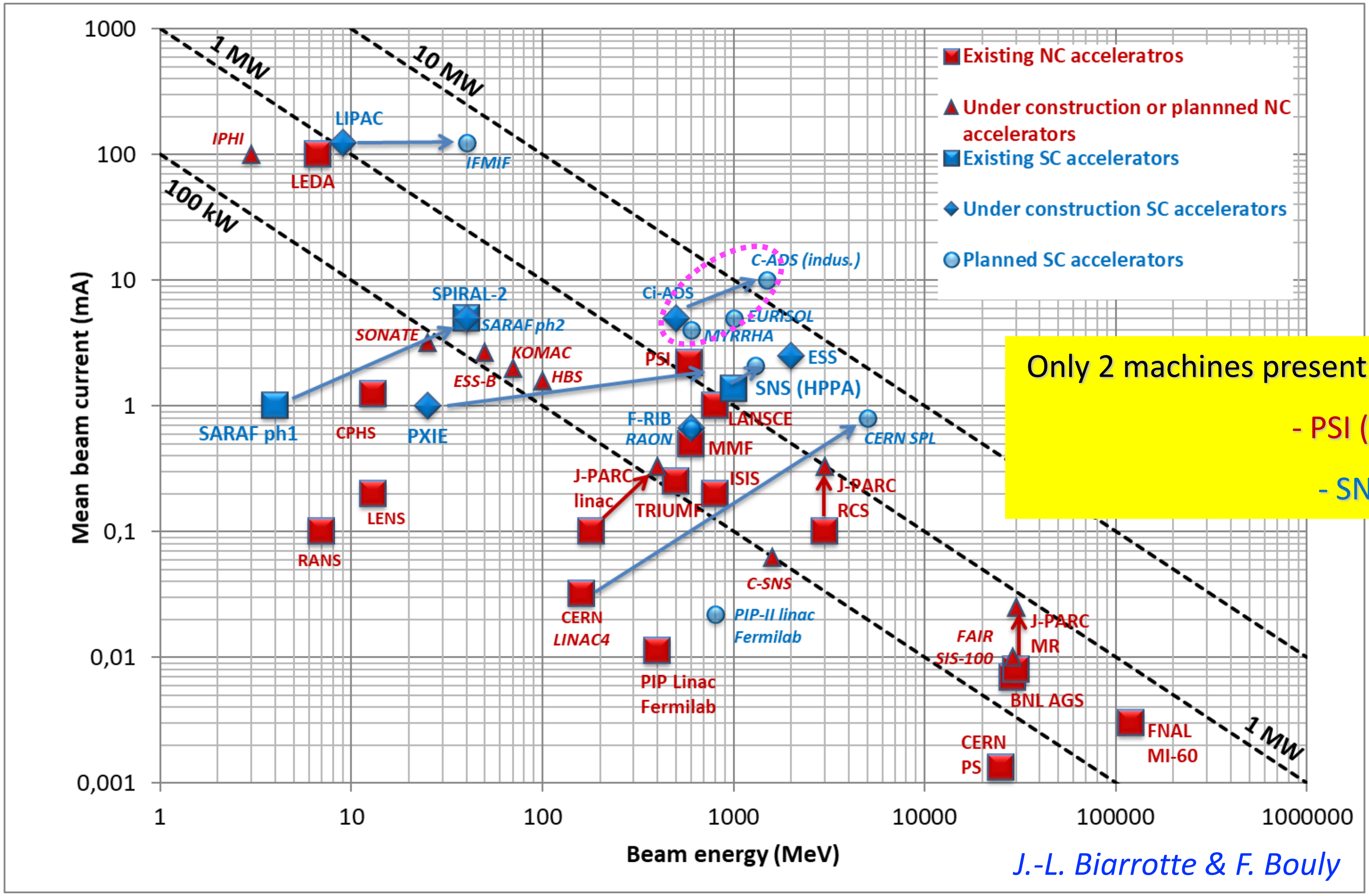
3. ACCELERATORS FOR HIGH POWER ADS

- Requirements
- High power accelerators
- ADS projects

Accelerators for high power ADS

- ADS demonstrator (tens of $MW_{th.}$) require high power (multi-MW) beam
- Beam loss must be controlled at an extreme level : **beam loss must be < 10^{-6} per meter typically**
- Main associated challenges of high power hadron accelerators
  - **Physics of intense hadron beams**
    - Management of space charge effects
    - Understanding and control of beam halo generation during transport
  - **Accelerator technologies**
    - Accelerating cavities (RFQ, superconducting cavities) and high power Radio-Frequency elements
    - Diagnostics for intense hadron beams
    - New generation targets (MegaWatt)
- **Additional challenge for ADS application : extreme level of reliability**
  - Accidental interruptions (beam trips) of multi-MW beam power create stress/fatigue on the fuel assemblies and affect the availability of the facility
  - **Accelerator by the interface with the nuclear core ➔ Beam trips « forbidden »**

Panorama of high power hadron accelerators



J.-L. Biarrotte & F. Bouly

Normal conducting

Superconducting

Only 2 machines presently operating above MW level:

- PSI (cyclotron)
- SNS (linac)

➔ superconducting linac = reference solution for power ADS

Main power ADS projects worldwide

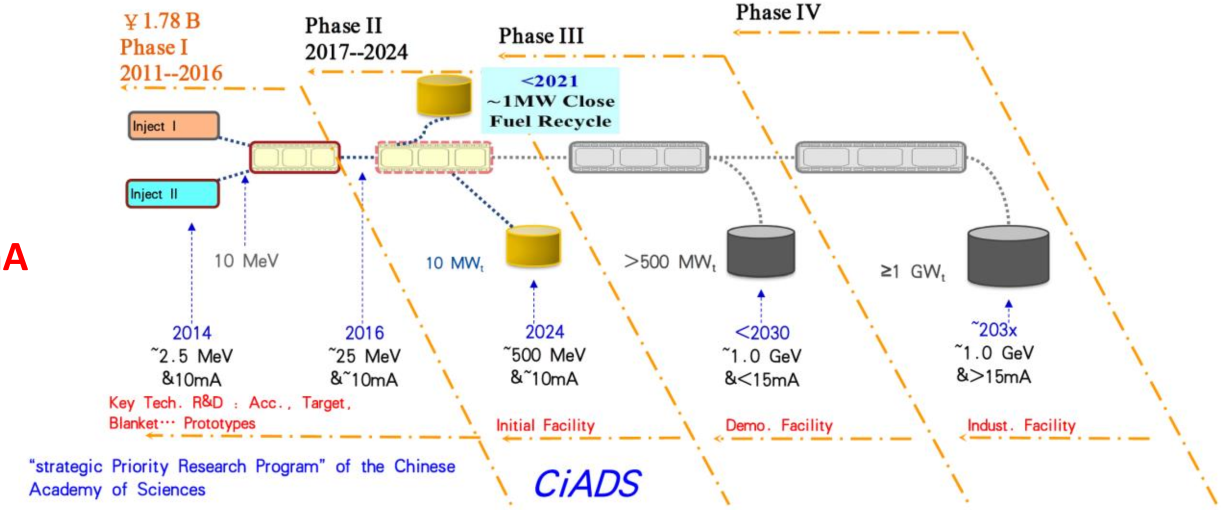
- **China**
  - **Ci-ADS at Institute of Modern Physics (IMP), 2.5 MW proton beam**
- **Europe**
  - **MYRHHA project at SCK-CEN in Belgium, 2.4 MW proton beam**
- Japan
  - Transmutation Experimental Facility : ADS Target Test Facility (TEF-T) at JPARC
  - 250 kW beam power (400 MeV proton), target Lead-Bismuth eutectic (LBE)
- Ukraine
  - ADS facility of Kharkov Institute of Physics & Technology (KIPT)
  - 100 kW electron beam power (100 MeV electrons) onto W or U targets + subcritical assembly (U fuel + Beryllium graphite reflector)
- India
  - Project Low Energy High Intensity Proton Accelerator (LEHIPA) at BARC
  - 600 kW proton beam (20 MeV, 30 mA) at BARC

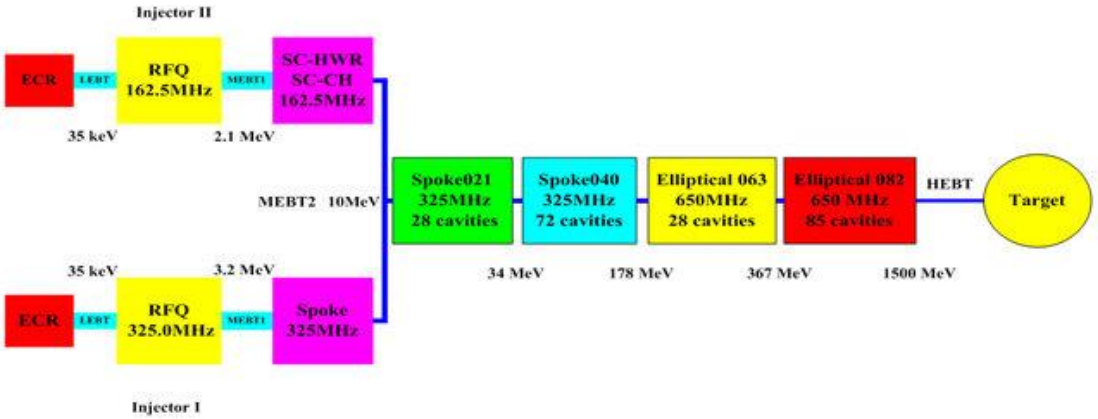
Chinese ADS (Ci-ADS)

- Chinese ADS (Ci-ADS) at Institute of Modern Physics (IMP)
- Project of ADS demonstrator with
  - a lead-bismuth eutectic cooled fast reactor with 7.5 MWth (keff = 0.97)
  - a granular flow target
  - superconducting proton linac
- Linac reference design
  - **2.5 MW proton beam : 500 MeV, 5 mA**

Design Particle	proton	
Energy	500	MeV
Beam current	5	mA
Beam power	2.5	MW
Operation mode	CW&Pulse	
Beam loss	< 1	W/m
Reactor power	7.5	MWt

- **Reliability requirements for the beam**
  - Trips < 10 s : -
  - 10 s < trips < 5 min : 2500/year
  - Trips > 5 min : 300/year

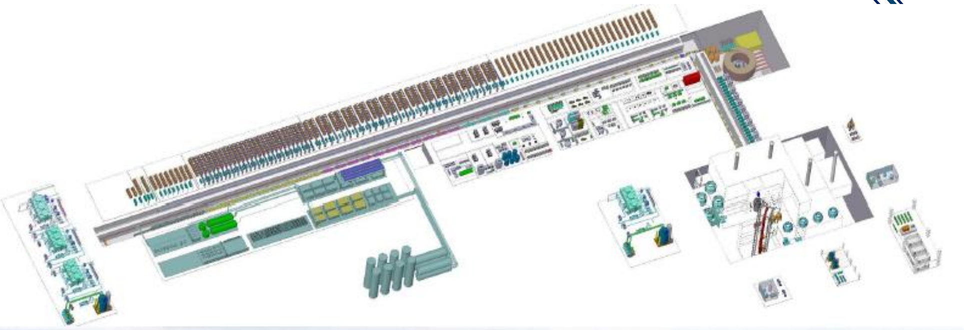




Yuan He, TCADS-4, Oct. 14-17, 2019, Antwerpen, Belgium

Chinese ADS (Ci-ADS) : project status

- Linac design performed



- Front end demo linac (CAFe) in operation since mid 2019
  - Injector section at 17.5 MeV and 2 mA
  - Availability = 89% over 5 days of operation at 17.5 MeV

CAFe injector

- Ground breaking in 2018

Yuan He, TCADS-4, Oct. 14-17, 2019, Antwerpen, Belgium

4. MYRRHA

- Project status
- Linac reference design
- Reliability
- Fault recovery
- Main R&D achievements

MYRRHA as an ADS demonstrator

- Goal : Demonstrate the physics and technology of an Accelerator Driven System (ADS) for transmuting long-lived radioactive waste at multi-MW level

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

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

Main features of the ADS demo

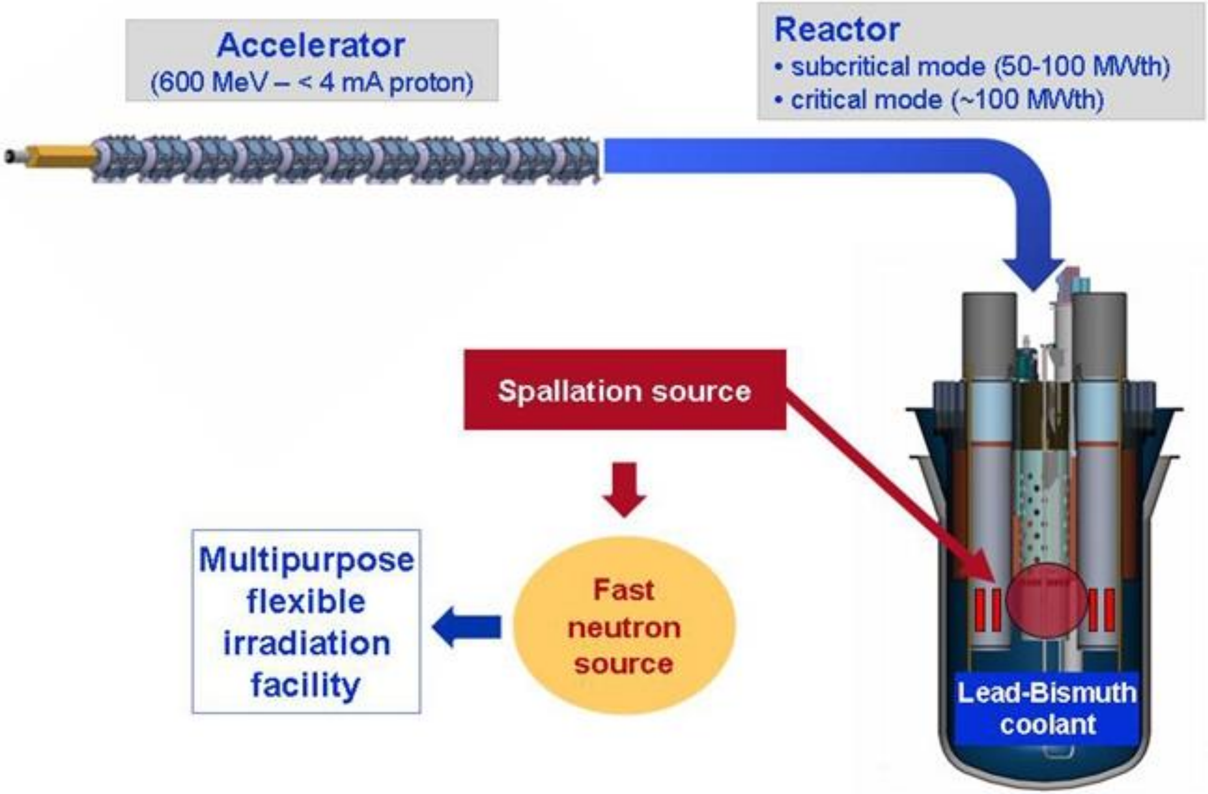
50-100 MWth power

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

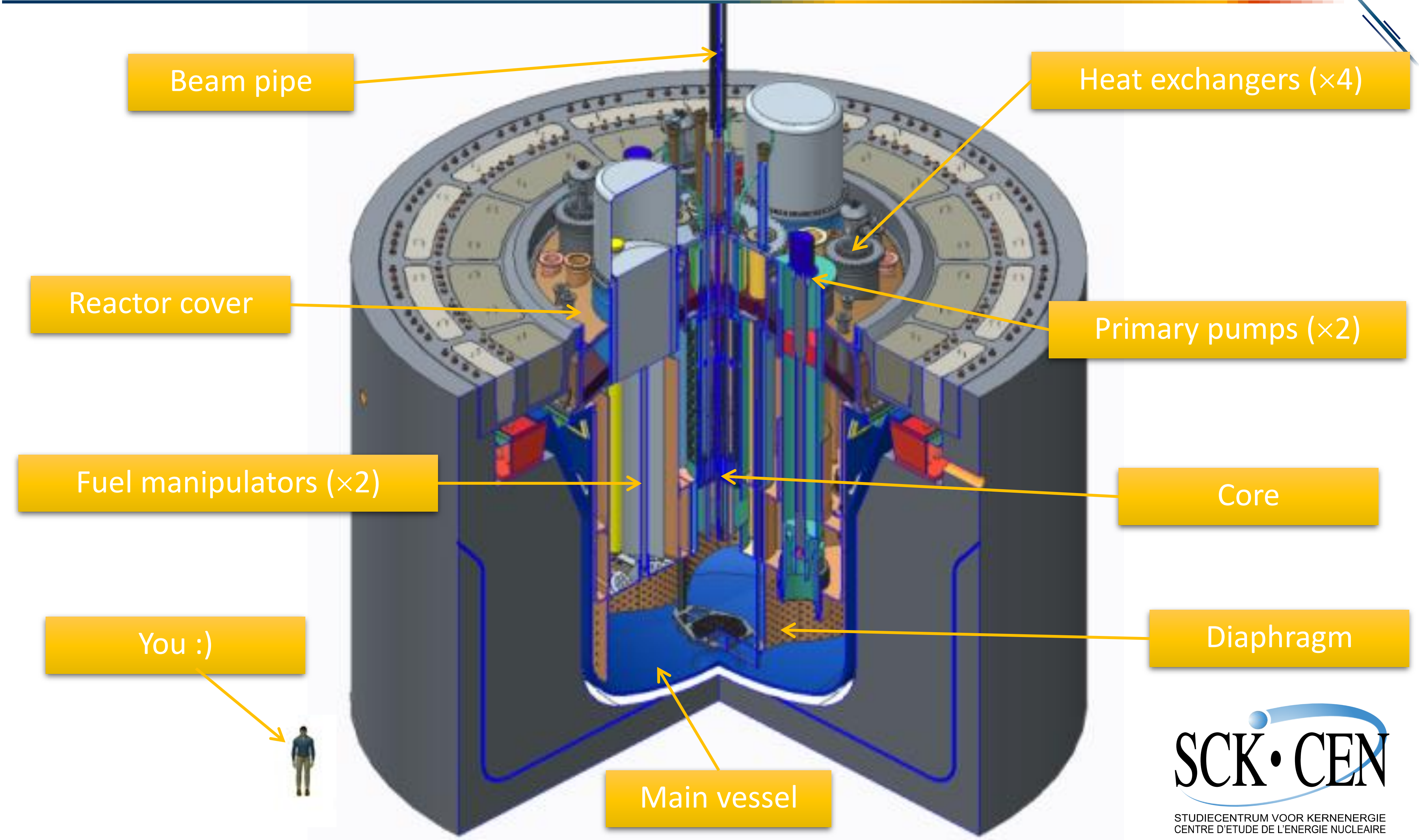


Accelerator
(600 MeV – < 4 mA proton)

Reactor
- subcritical mode (50-100 MWth)
- critical mode (~100 MWth)

MYRRHA = 600 MeV, 4 mA proton linac + LBE target + reactor

MYRRHA reactor layout (v1.6)



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MYRRHA supported by the Belgian government

- 2014 : The Belgian Government supports in a progressive way the MYRRHA project

- **2018 : Belgium allocated 558 M€ for 2019-2038 to fund MYRRHA phase 1**
  - **Phase 1 : MINERVA (M**YRRHA **I**sotopes productio**N** coupling the lin**E**ar accele**R**ator to the **V**ersatile proton target f**A**cility)
  - MINERVA : Coupling the MYRRHA 100 MeV linac to a Proton Target Facility (PTF)

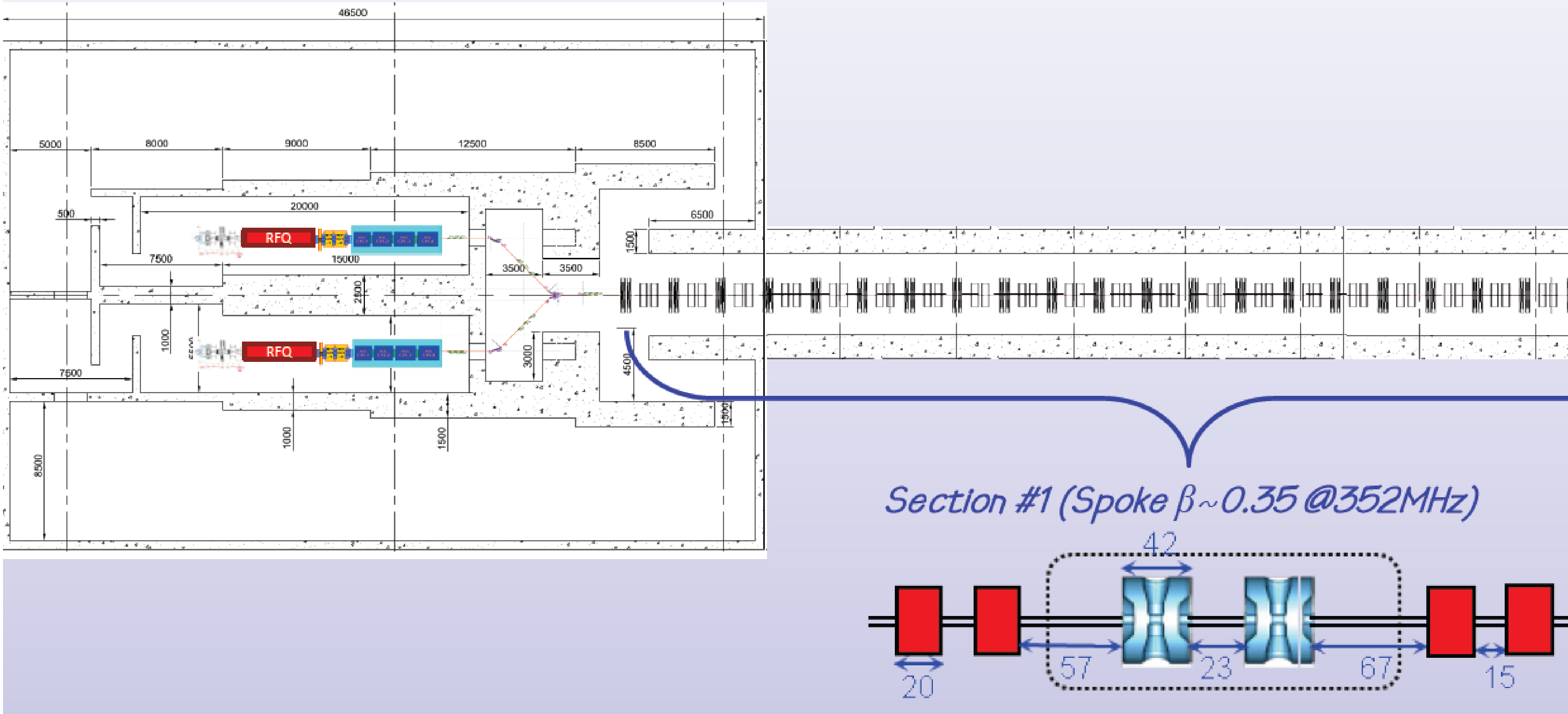
- Applications of MINERVA
  - Production of medical radioisotopes for targeted cancer therapy
  - Fundamental physics: high-precision, high-statistics experiments (nuclear, condensed matter, biology…)
  - Material irradiation for Fusion

- Goals of MINERVA
  - Validation of the technological choices
  - Representative unit of the full MYRRHA linac (600 MeV)
  - Implementation of fault tolerant schemes
  - Evaluation of the reliability goal for the full MYRRHA linac

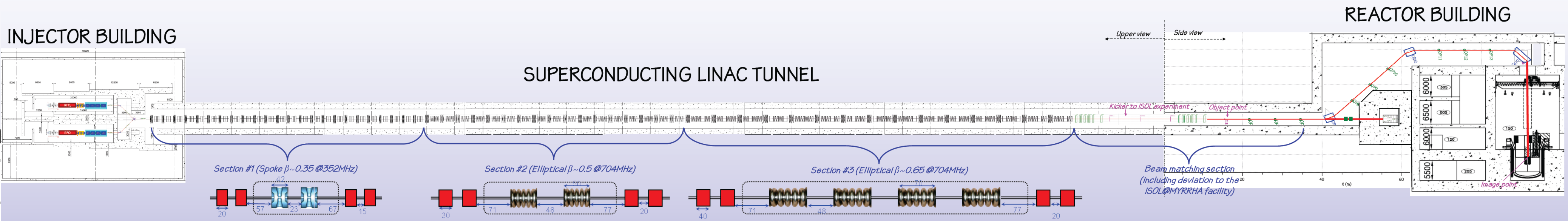
MYRRHA phase 1 (MINERVA) = 100 MeV linac + proton target by 2026

Layout of the 600 MeV MYRRHA linac

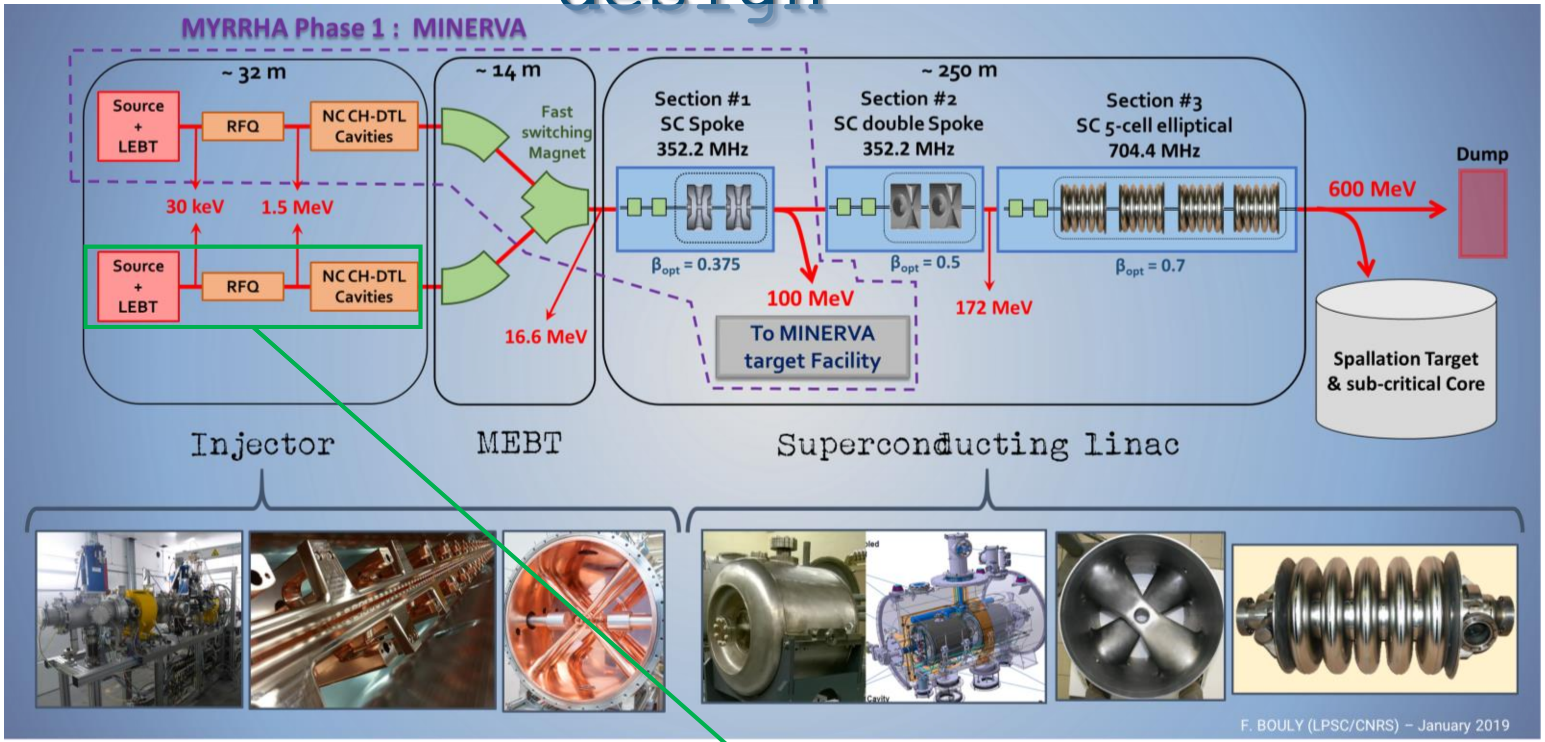
INJECTOR BUILDING



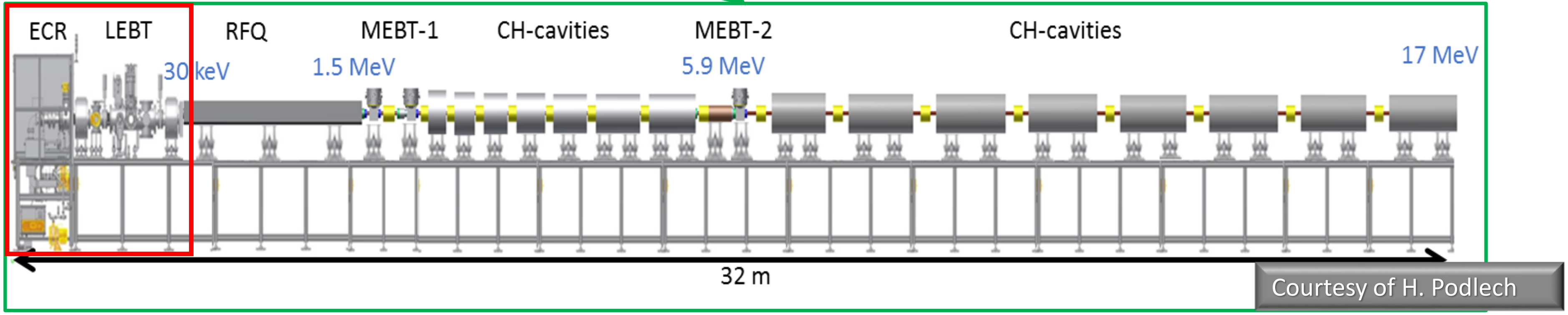
Layout of the 600 MeV MYRRHA linac



MYRRHA linac reference design



F. BOULY (LPSC/CNRS) – January 2019



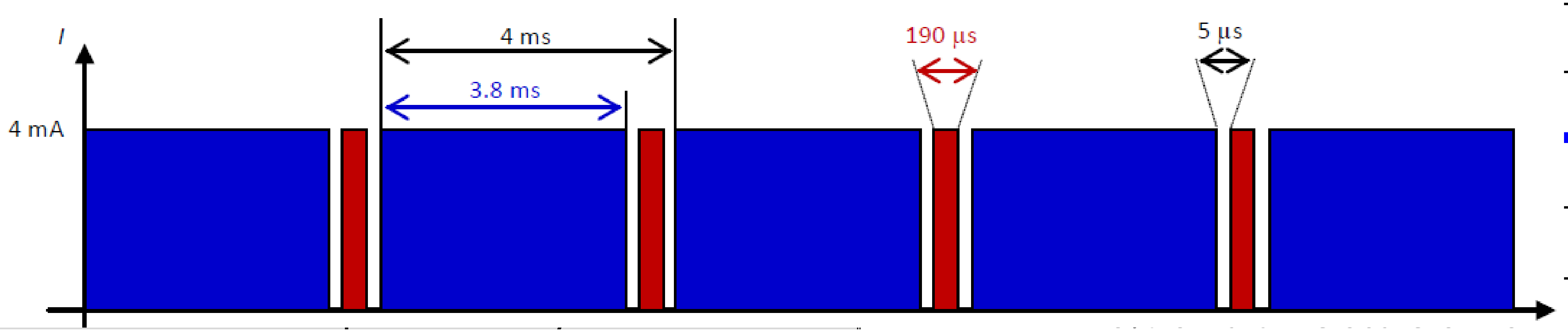
Courtesy of H. Podlech

F. Bouly, MRYTE WP2 final meeting, October 2018

Requirements for the Accelerator

→ High power proton beam (up to 2.4 MW)

Proton energy	600 MeV
Peak beam current	0.1 to 4.0 mA
# of a	eriod
# of allowed beam trips on reactor longer than 0.1 sec	100 maximum per day
# of allowed beam trips on reactor shorter than 0.1 sec	unlimited



Reference MYRRHA beam time structure for 2.4 MW operation:
-> long 4mA blue pulses are sent to the reactor (mean power is adjusting with pulse length)
-> short red ones are sent to ISOL (creating 200us beam holes for reactor subcriticity monitoring)

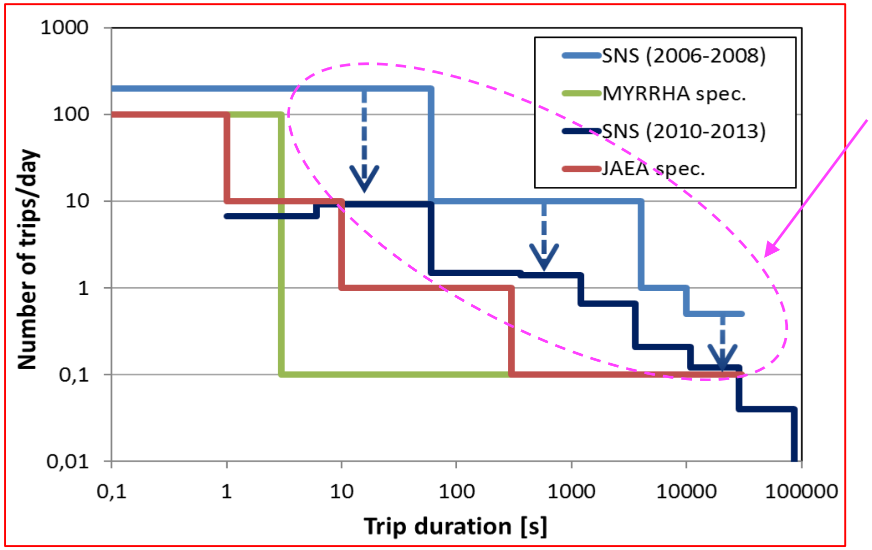
→ Extreme reliability level

Reliability

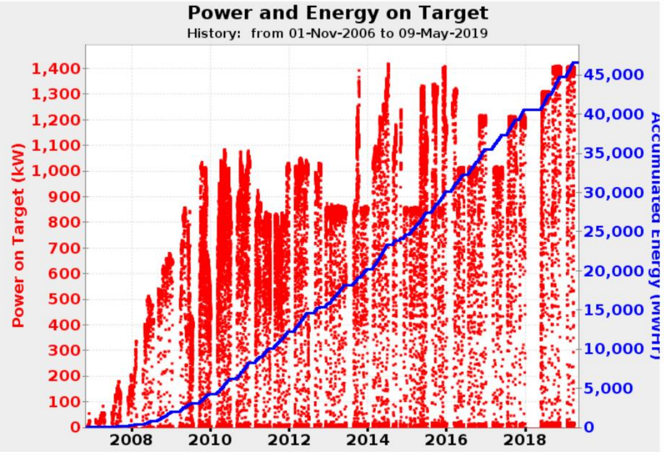
- **MYRRHA** reliability requirements
  - to minimize thermal stress & fatigue on target window, reactor structures & fuel assemblies
    - derived from the PHENIX reactor operation analysis
  - To ensure an 80% availability of facility : given the foreseen reactor start-up procedures
    - Approximately 24h to restart the reactor

  ➔ **Less than 10 beam trips longer than 3 sec over 3 months of operation (or 0,1 beam trips/day)**

- Improvements of reliability through the commissioning and the machine operation
  - It will take time to reach a ligh level of reliability



Significant improvement of SNS within 4 years



J. Galambos, "Operations Experience of SNS at 1.4 MW and Upgrade Plans for Doubling the Beam Power", in Proc. 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019.

F. Bouly et al., " The MYRRHA Superconducting linac Fault-tolerant design and developments", TCADS-4 Workshop, Antwerp, Belgium , 2019
D. Vandeplassche et al., "Accelerator Driven Systems", Proc. IPAC 2012, New Orleans Louisiana, USA, 2012

Reliability guidelines

Reliability guidelines are required to design an ADS accelerator :

- **Robust design :**

➢ **Robust optics**: focussing current-independent, large acceptance, minimise loss, no resonance crossing

➢ **Conservative design** : all components will be operated well below their physical limits (derating)

➢ Make it as simple as possible

➢ Low thermal & mechanical stress

➢ Careful choice of ancillary system : pumps, cooling systems, etc..

- **Reparability**

➢ **On-line where possible**

➢ Efficient maintenance scheme (MYRRHA : 1 month maintenance vs. 3 month operation)

- **Redundancy**

➢ **Serial** where possible (linac), or **parallel** (injector) even for ancillary systems

➢ **Failures** can be tolerated but must be **mitigated** to guaranty a **high fault tolerance**

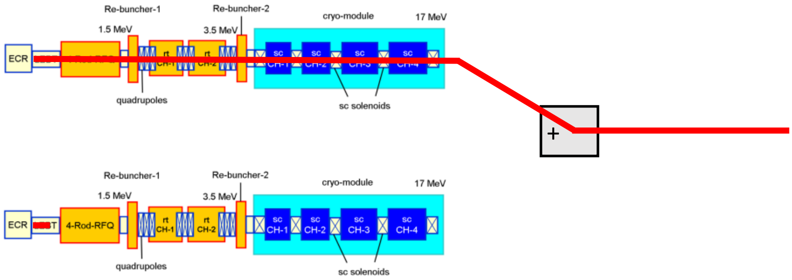
➢ **Fault compensation scheme** : Introduced during design studies of the MYRRHA accelerator, requires margins

J.-L. Biarrotte, D. Uriot, "Dynamic compensation of an RF cavity failure in a superconducting linac", Physical Review ST: A&B, 2007

Strategy for a fault in the injector = parallel redundancy

❶ Initial configuration

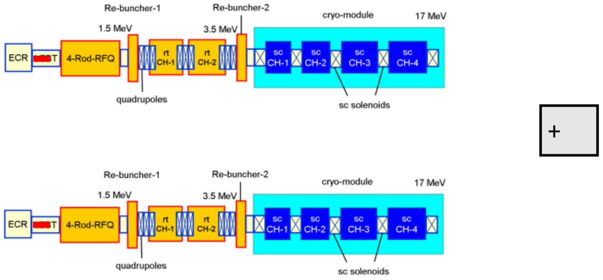
Operational injector 1: RF + PS + beam ON



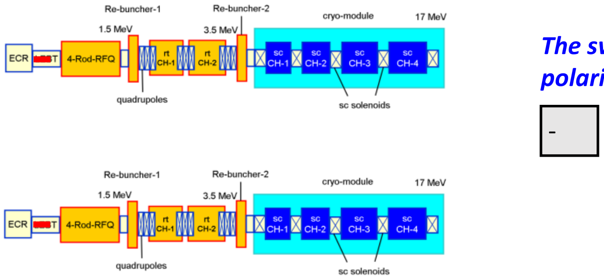
Warm stand-by injector 2: RF+ PS ON, beam OFF (on FC)

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 1

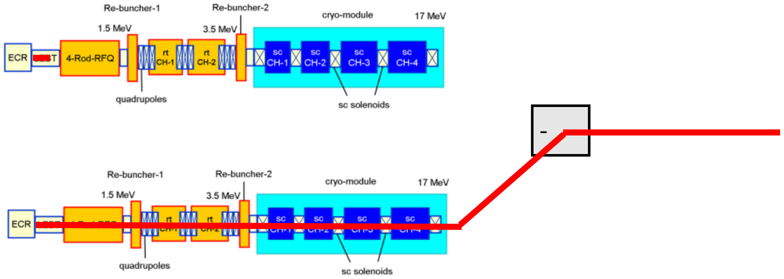


The switching magnet polarity is changed (~1s)

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 in the main linac = serial redundancy

❶ A failure is detected anywhere

→ Beam is stopped by the MPS in injector at t_0

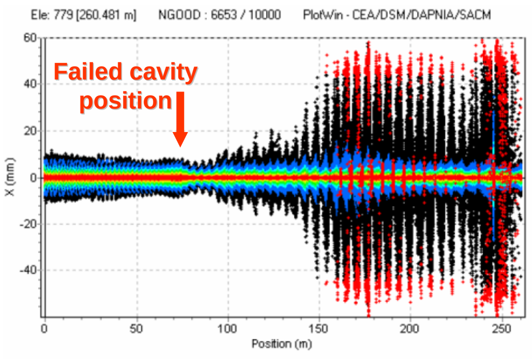


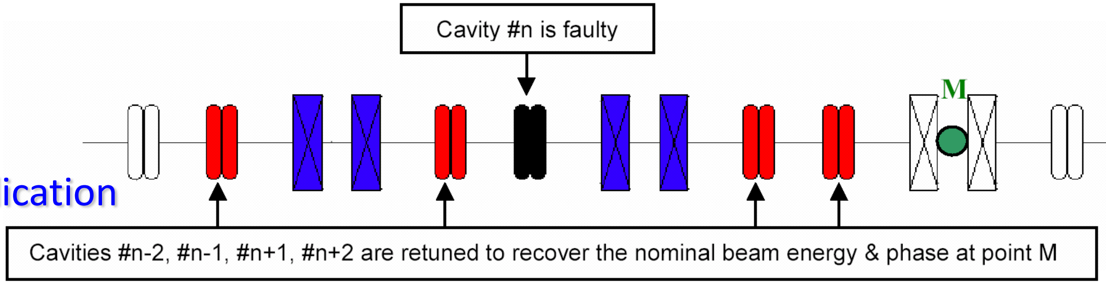
Figure 12 : Transverse beam distribution at 220 µs, in red are plotted the losses

❷ The fault is localized in a SC cavity RF loop

→ Need for an efficient fault diagnostic system

❸ New V/ϕ set-points are updated in cavities adjacent to the failed one

→ Set-points determined via virtual accelerator application and/or at the commissioning phase


Cavity #n is faulty

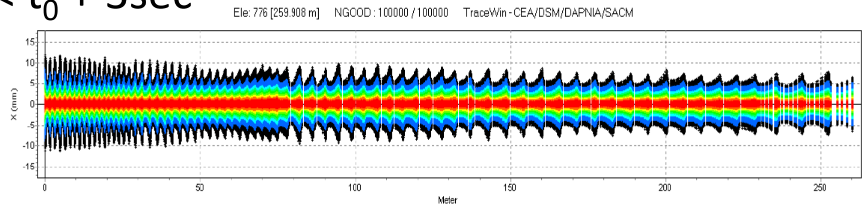
Cavities #n-2, #n-1, #n+1, #n+2 are retuned to recover the nominal beam energy & phase at point M

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

→ Using the Cold Tuning System

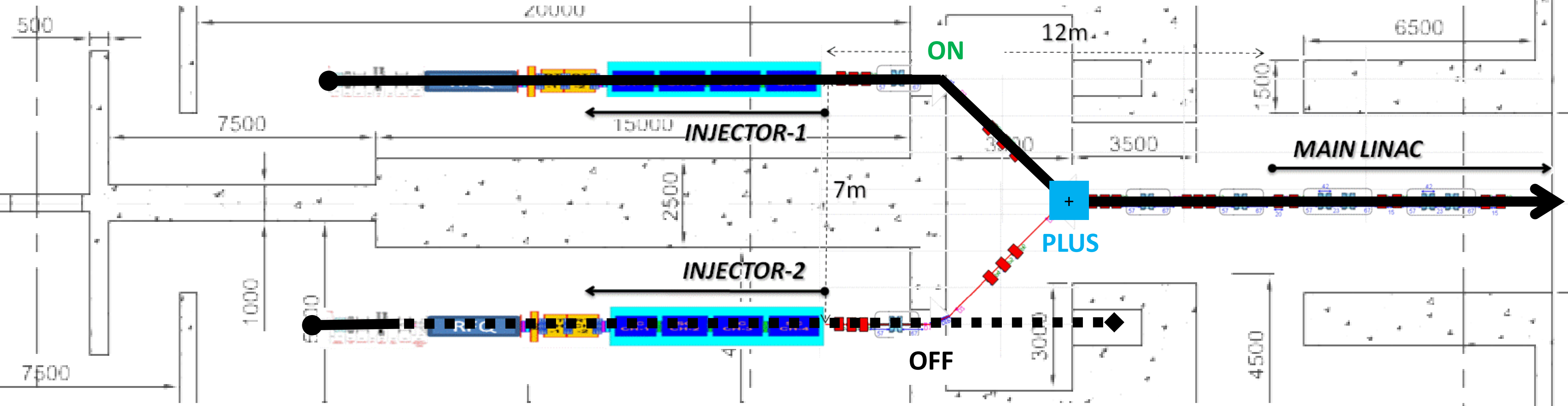
❺ Once steady state is reached, beam is resumed at $t_1 < t_0 + 3\text{sec}$

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



Injector beam reconfiguration (1/4)

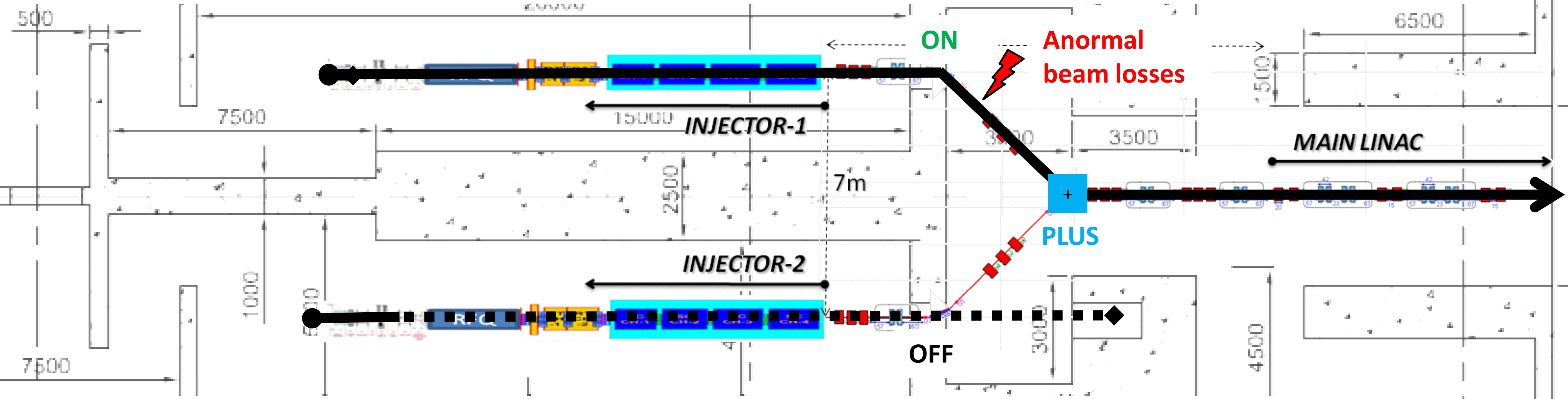
- **Injector 1 in nominal operation mode : beam sent to main linac**
  - ✓ All elements operating (source, RF, power supplies…) at nominal parameters
  - ✓ Chopper: nominal mode (i.e. pseudo CW with short holes)
  - ✓ Switching magnet: power supply polarized PLUS



- **Injector 2 in stand-by mode: beam sent to dump #2**
  - ✓ All elements operating at nominal parameters except dipole magnet
  - ✓ Chopper: tuning mode (i.e. low duty cycle tbd)
  - ✓ Survey of output beam properties (TOF energy, current monitor)

Injector beam reconfiguration (2/4)

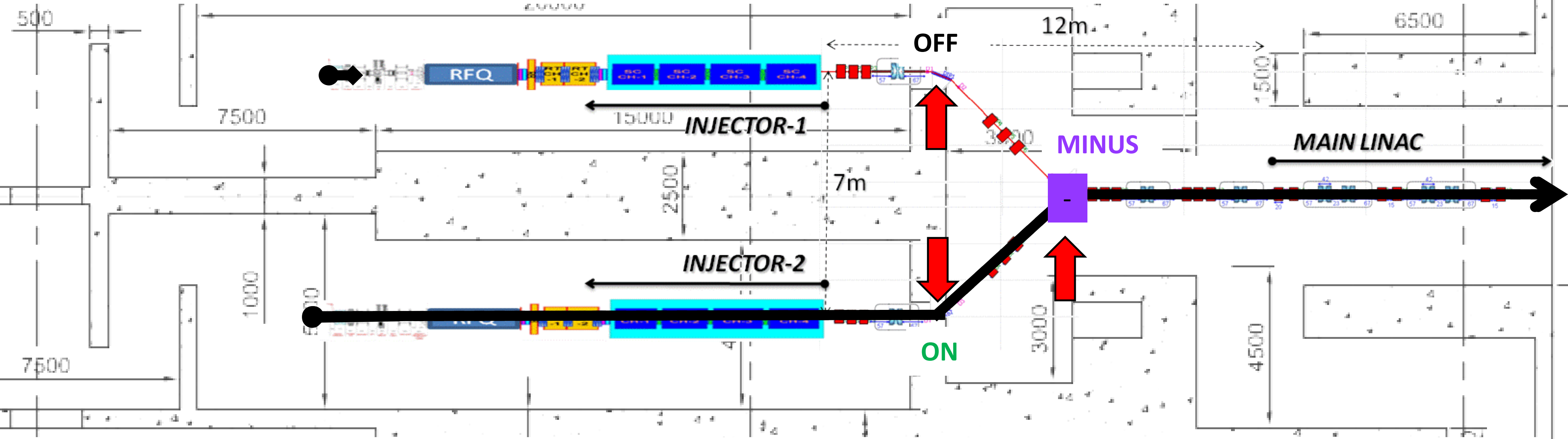
- **A failure is detected in Injector #1**
  - ✓ E.g. anormal beam losses in MEBT (or source voltage breakdown, PS failure, cavity quench…)
  - ✓ Fault information is sent to Machine Protection System (MPS) / Control System
  - ✓ If failure is serious (i.e. reproducible after 1 or 2 tries), MPS stops the beams



- **MPS stops the beam in both injectors asap (typically less than 0.1ms)**
  - ✓Using the LEBT chopper only in Injector #2
  - ✓Definitively in injector #1 using (TBD) the LEBT chopper as a fast mean and then the LEBT Faraday cup for example as a slow & permanent mean

Injector beam reconfiguration (3/4)

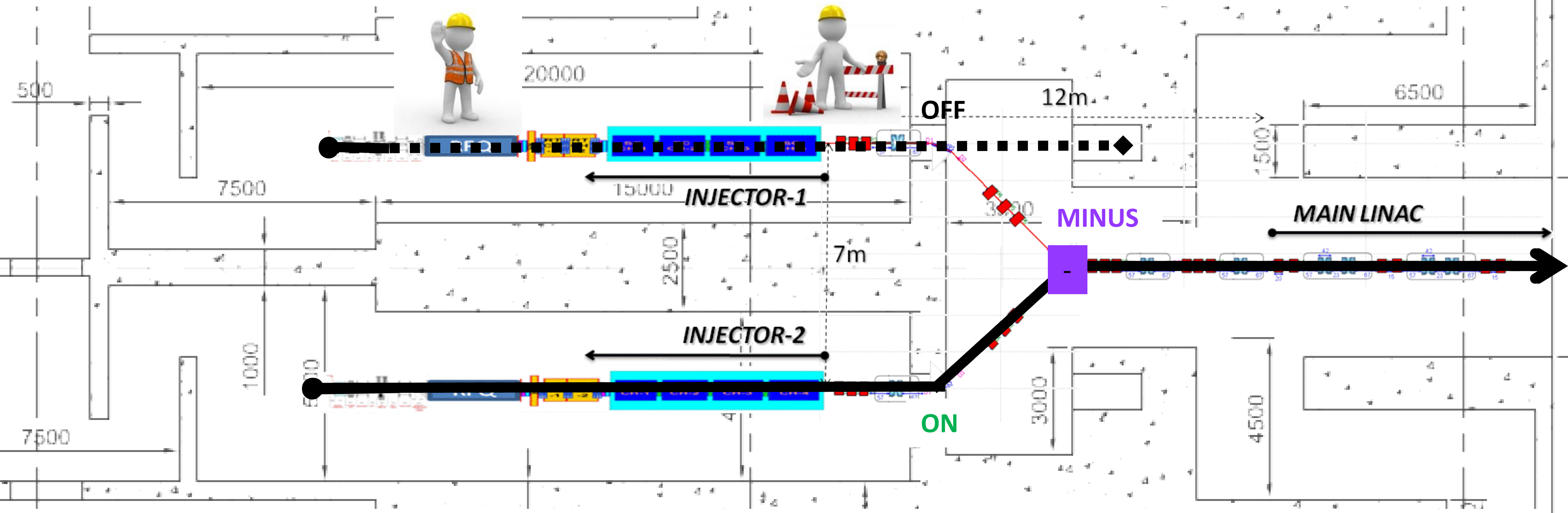
- **The polarity of dipole magnets is changed (time budget = less than 1sec tbc)**
  - ✓ Dipole of injector #1 is switched OFF
  - ✓ Dipole of injector #2 is switched ON
  - ✓ Common dipole polarity is changed to MINUS



- **Once steady-state is reached in the PS, beam is resumed in Injector #2**
  - ✓ First, a few very short pulses are sent to check everything is ok (« fast commisionning mode »)
  - ✓ If all is ok, then duty cycle is ramped quickly (within 1 or 2 sec) to recover nominal operation

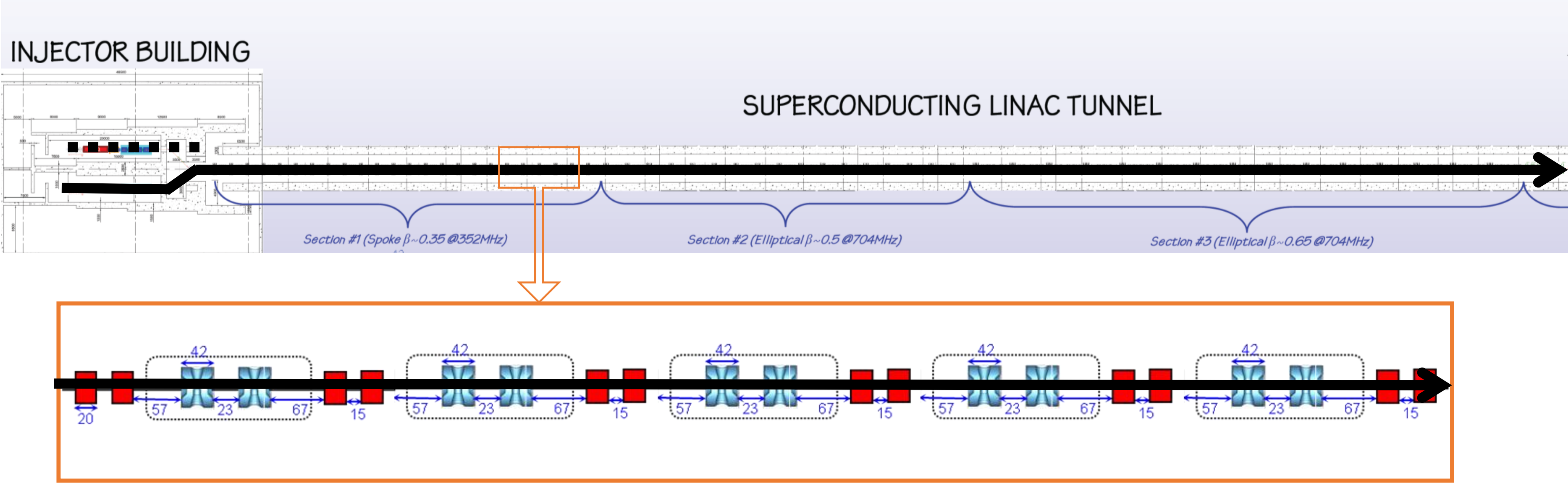
Injector beam reconfiguration (4/4)

- **Maintenance is started on Injector #1**
  - ✓ Injector #1 casemate needs to be accessible during Injector #2 operation
  - ✓ Beam might probably need to be completely stopped on Injector #1



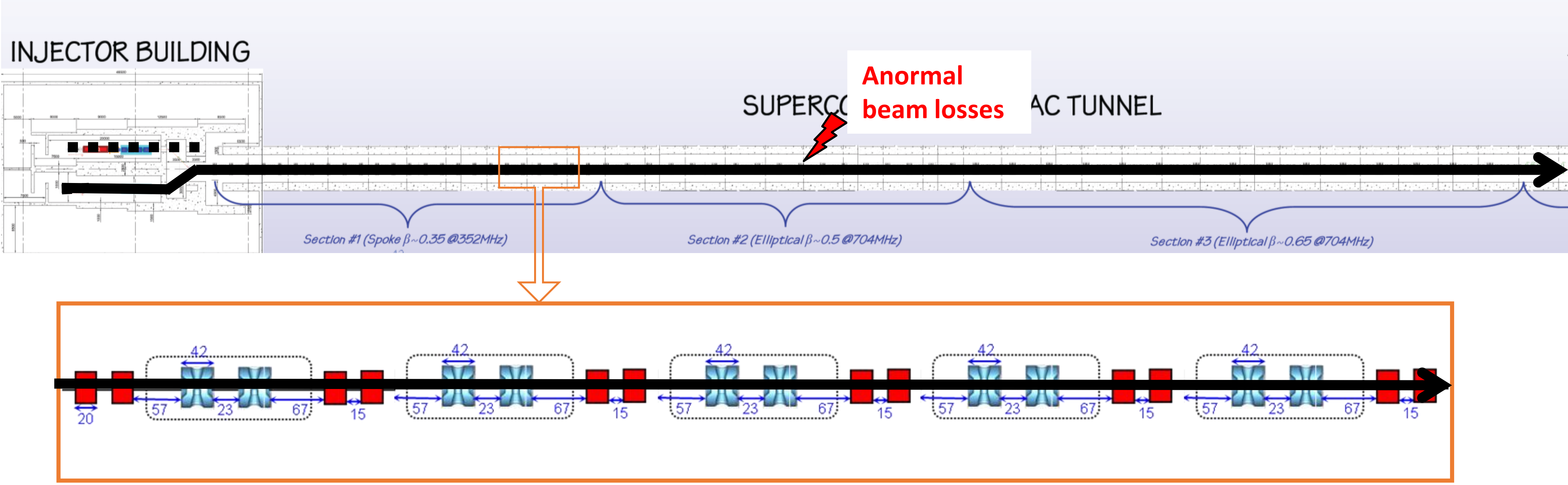
- **Once failed component is fixed, Injector #1 is put back to operation**
  - ✓ Injector #1 is re-tuned & commissionned localy
  - ✓ Once ok, injector #1 stays in « stand-by mode », low dc beam sent to beam dump #1

Main linac beam reconfiguration (1/6)



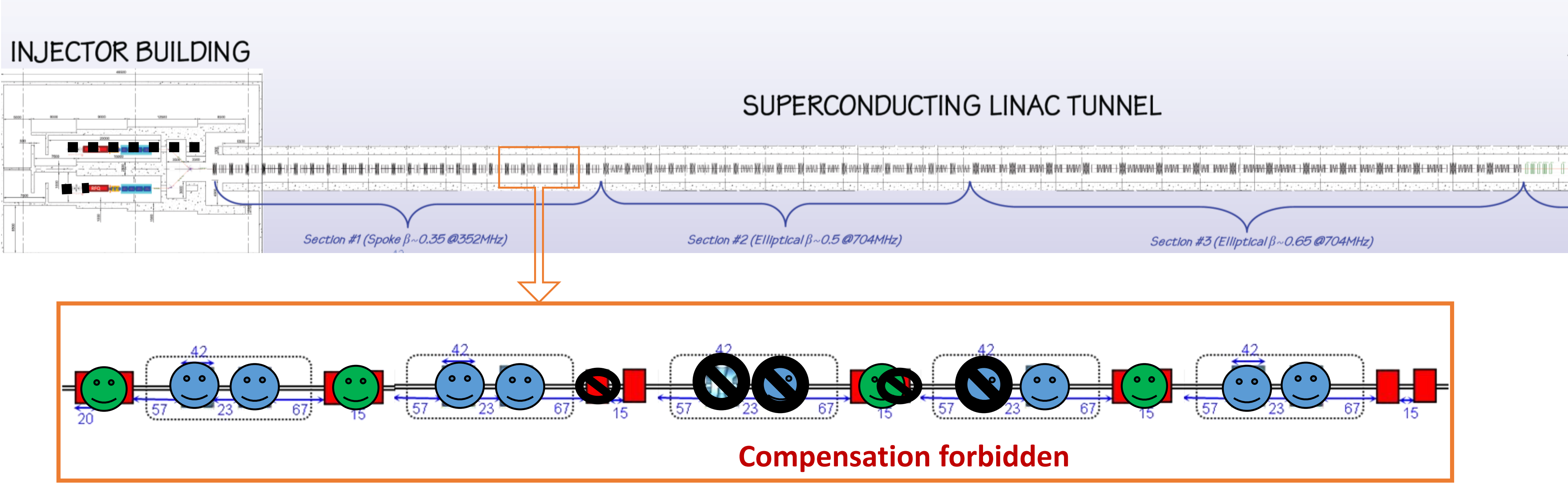
- **Nominal main linac operation**
  - ✓ All elements (cavities, RF amps, power supplies…) operating at nominal (derated) parameters
  - ✓ Reference scheme: local compensation scheme for RF & magnets faults
    about 30% margins available on all cavities, 40% on amplifiers & 10% on magnets PS

Main linac beam reconfiguration (2/6)



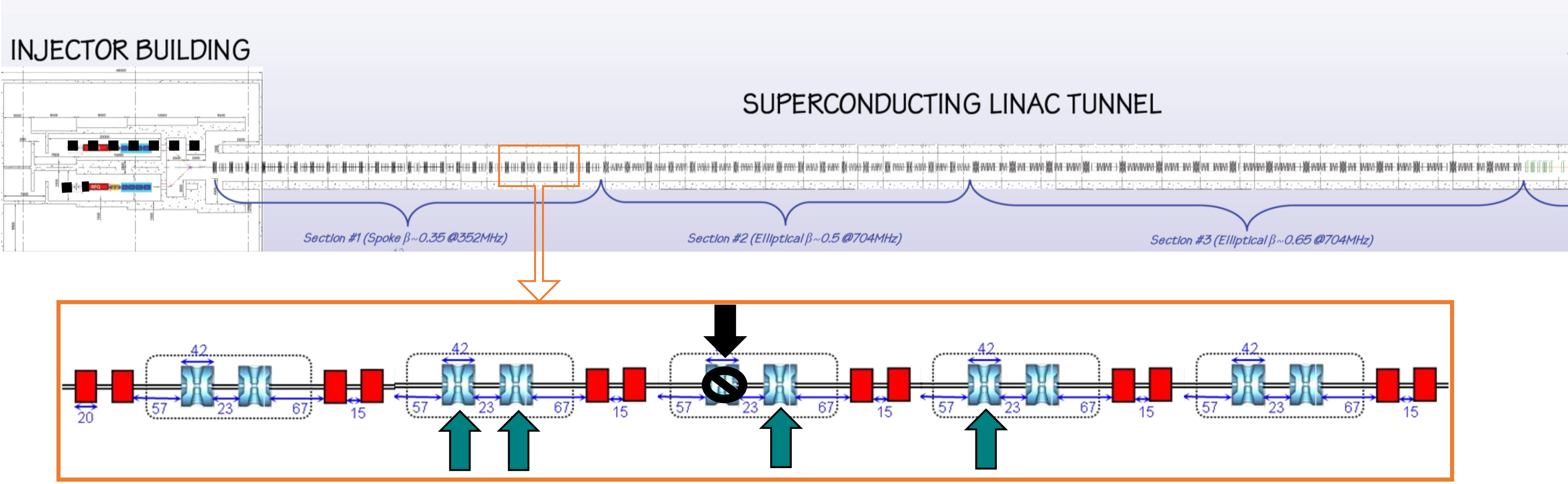
- **A fault is detected in the main linac**
  - ✓ E.g. anormal beam losses at high energy (or RF failure, PS failure…)
  - ✓ Fault information is sent to Machine Protection System (MPS) / Control System
  - ✓ If failure is serious (i.e. reproducible after 1 or 2 tries), MPS stops the beams
- **MPS stops the beam in the operating injector asap**
  - ✓ Using the LEBT chopper + possibly an additional redundant mean (tbd)

Main linac beam reconfiguration (3/6)



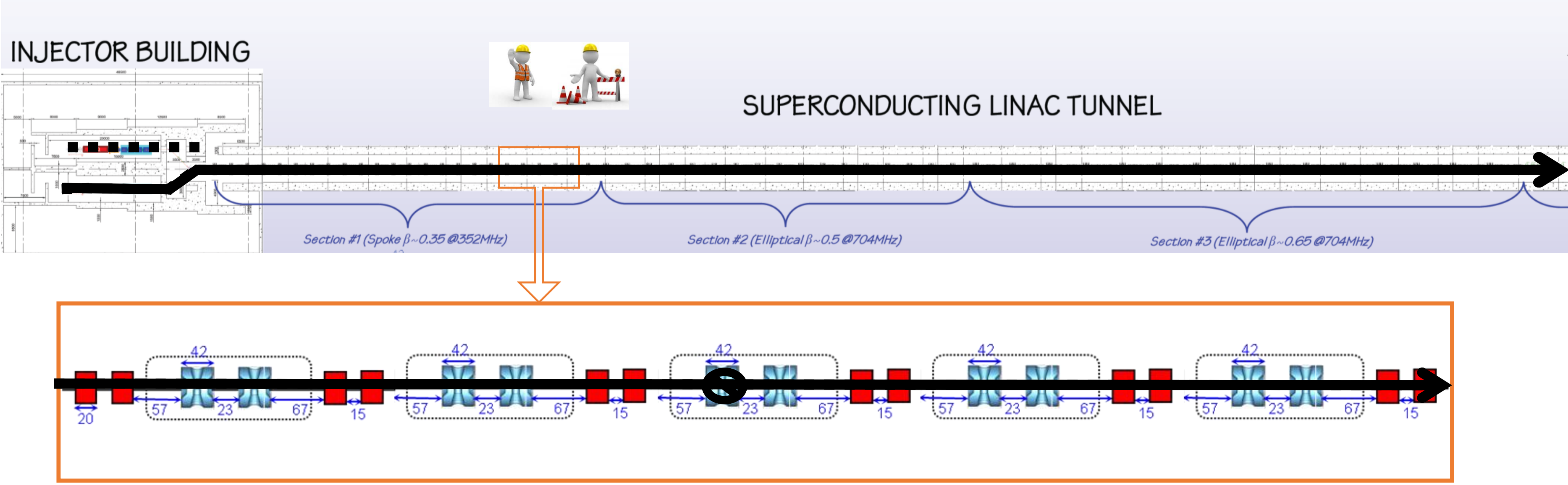
- ➢ **The origin of the fault is analysed & fault recovery procedure is launched if possible**
  - ✓ If the origin of the fault is not diagnosed, the beam needs to be stopped permanently
  - ✓ If it is diagnosed AND can be compensated, fault recovery procedure can be started
  - ✓ Conditions to fullfil to make compensation possible (proposed basic preliminary rules):
    - ○ fault implying a **cavity**: the 4 nearest neighbouring cavities operating derated (i.e. not already used for compensation) are used; max allowed # of consecutive failed cavities = 2 (sections #1&2) or 4 (section #3)
    - ○ fault implying a **Qpole**: the whole doublet is switched off & the 4 neighbouring doublets are used; max allowed # of consecutive failed doublets = 1

Main linac beam reconfiguration (4/6)



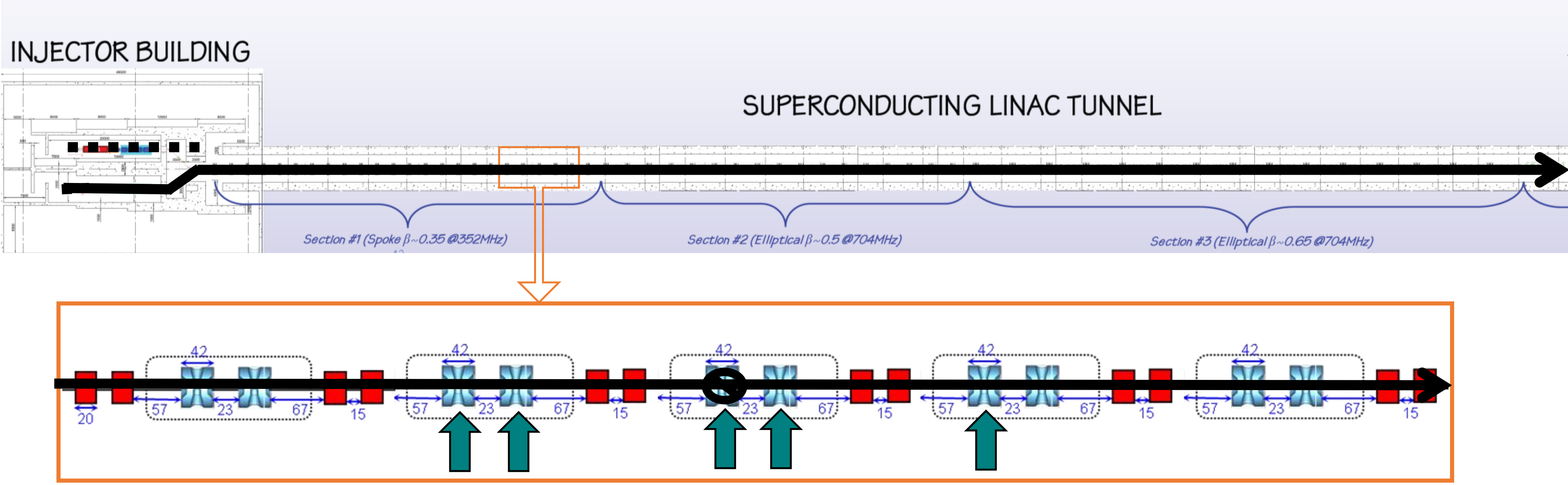
- **Fast retuning procedure (e.g. case of a RF cavity failure)**
  - ✓The failed cavity RF loop is disabled
  - ✓ The failed cavity is detuned of more than 100 bandwidth (time budget = less than 2 seconds)
  - ✓New (Voltage / Phase) setpoint values for compensating cavities are picked in the Control System database (from past beam experience or from a predictive calculation)
  - ✓ New setpoints are applied in the corresponding LLRF (w/ typically a ramp of about 150ms)
    - ○ To ensure capability of SC cavities to raise reliabily, its operating voltage has to be checked at each maintenance period !

Main linac beam reconfiguration (5/6)



- **Once steady-state is reached on the retuned elements, back to beam operation**
  - ✓First, few very short pulses are sent to check everything is ok (« fast commisionning mode »)
  - ✓If all is ok, then duty cycle is ramped quickly (within 1 or 2 sec) to recover nominal operation
- **Maintenance is done if possible**
  - ✓If the needed maintenance is inside the tunnel -> wait for next shut-down period
  - ✓If the needed maintenance is outside the tunnel -> repair during beam operation

Main linac beam reconfiguration (6/6)

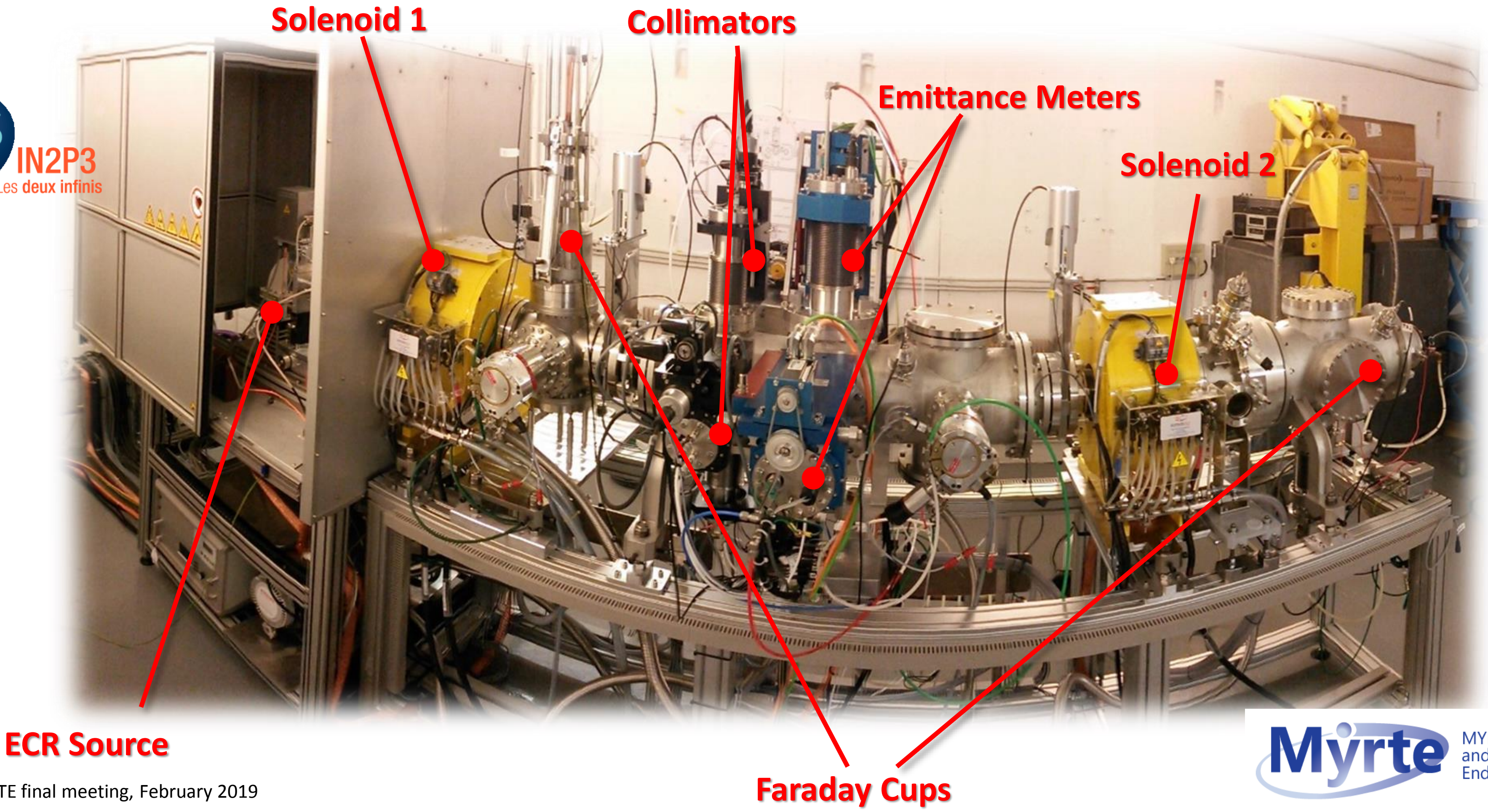


- ➢ **If maintenance is successful, back to nominal operation using opposite procedure (? TBC)**
  - ✓Beam is stopped
  - ✓ The repaired cavity is retuned (time budget = less than 2 seconds)
  - ✓Initial (Voltage / Phase) setpoint values for repaired & compensating cavities are set back
  - ✓ Beam is resumed (short pulse) and duty cycle is ramped up to nominal operation

Commissioning of ion source and LEBT

Design and construction of low energy beam transport line (LEBT) from ion source to RFQ

- LEBT developped by CNRS/IN2P3 (LPSC/Grenoble)
- Experimental program performed : studies of space charge compensation and halo control
- Shipped to Louvain-la-Neuve (Belgium) end of 2017, under operation since then



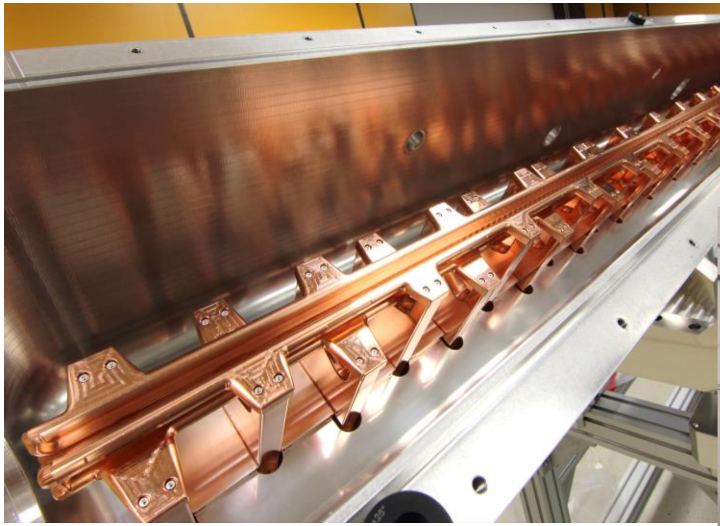
F. Bouy, MYRTE final meeting, February 2019

Realization of MYRRHA full-size RFQ

⟐ Design and construction of the RFQ for one injector

- 4-Rod structure was selected, operation at 176 MHz
- Conservative design (moderate voltage, thermal load less than 26 kW/m) by IAP Frankfurt
- Beam dynamics optimization with emphasis on longitudinal phase space
- RF tests perfomed in Frankfurt
- Under commisioning in Louvain-la-Neuve, Belgium

Parameter	Value	Unit
RF Structure	4.Rod	---
Frequency	176.1	MHz
Beam current	5	mA
Duty factor	100	%
E_{out}	1.5	MeV
R_p	72	kΩm
RF Power	113	kW
Specific power	26.5	kW/m
Voltage	44	kV
Length	4	m



H. Podlech, MYRTE final meeting, February 2019

MYRRHA Research and Transmutation Endeavour

Construction of a prototype solid state RF power amplifier

- **Development & construction of a 190 kW solid state CW amplifier @ 176 MHz**
- The RF system is critical regarding reliability
- Solid state amplifiers (SSA) can provide
  - High reliability
  - High reparability
- SSA built, tested (P=192 kW) by IBA
- Under tests at Louvain-la-Neuve

6 kW module

190 kW cabinet

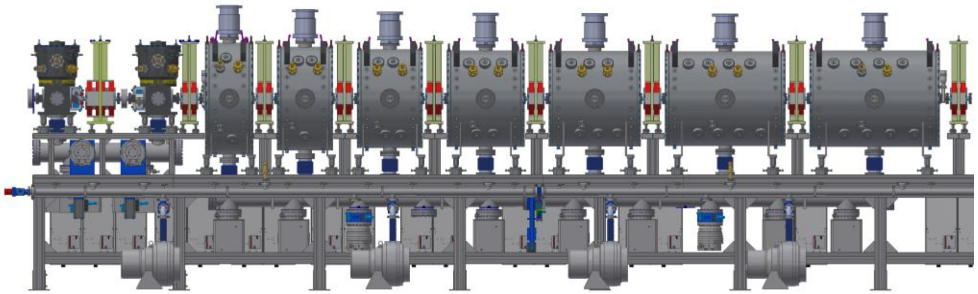
H. Podlech, MYRTE final meeting, February 2019

MYRRHA Research and Transmutation Endeavour

CH demonstration of room temperature CH cavities

Design and prototyping of a room temperature CH-cavities for the injector by IAP Frakfurt

- Beam dynamics simulations
- RF design of innovative RT CH-cavities
- Successful test of a MYRRHA-type RT CH-cavity
    - Operation at 35 kW/m at Frankfurt



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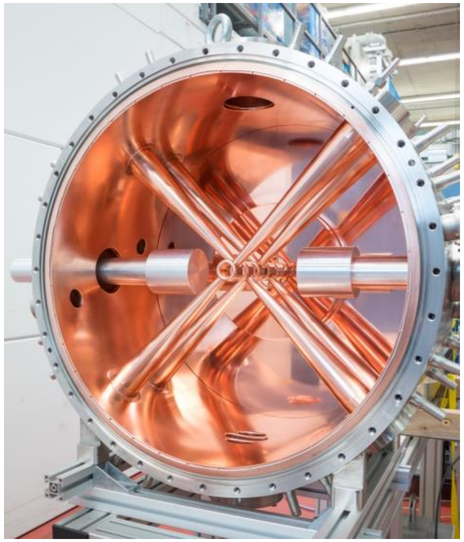
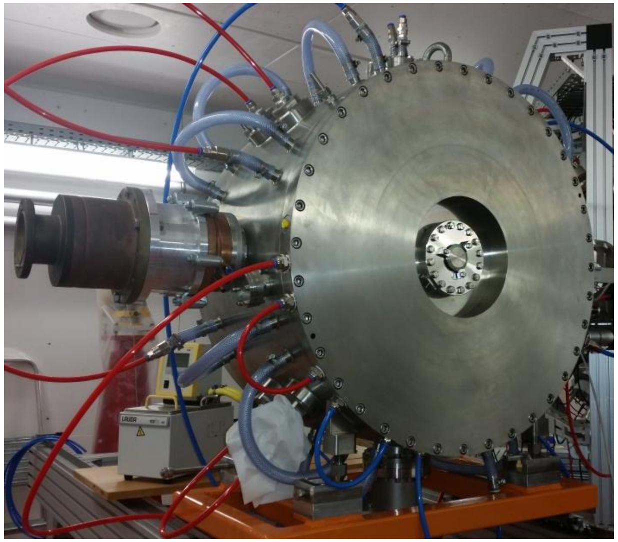
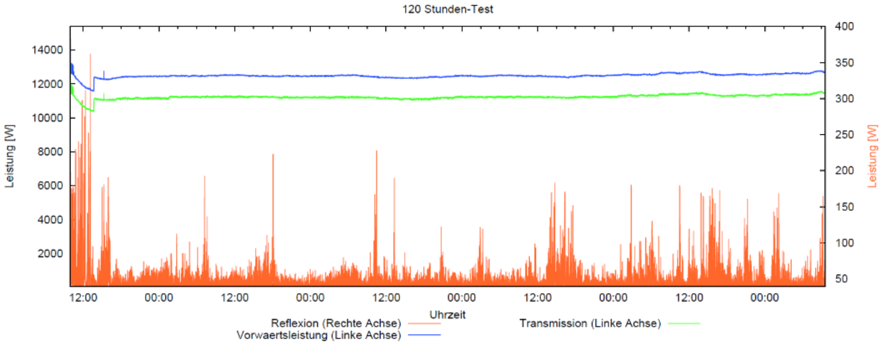






Cavity power/transmission versus time

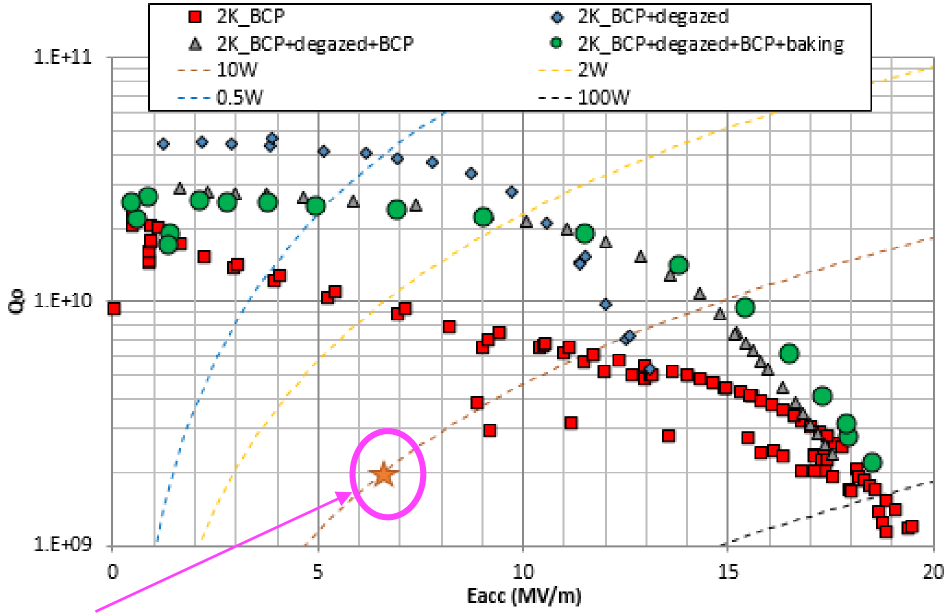
H. Podlech, MYRTE final meeting, February 2019

MYRRHA Research and Transmutation Endeavour

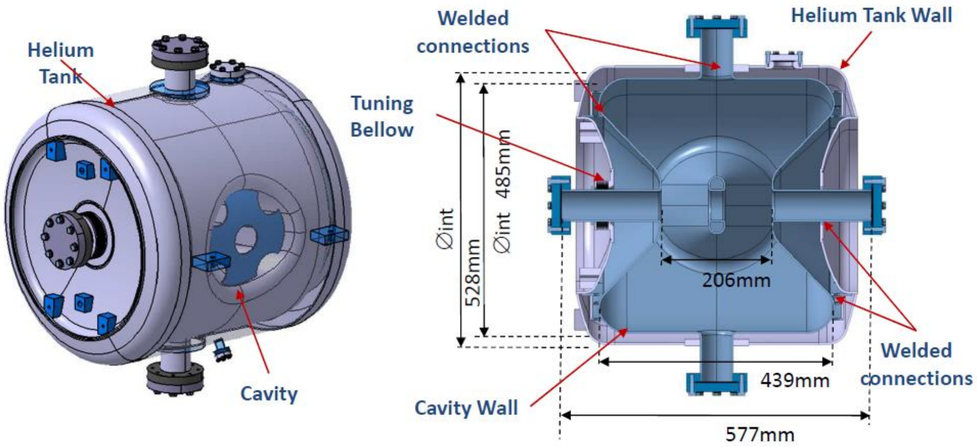
R&D on SRF Spoke cavities

Design and prototype superconducting Spoke cavities for the linac by CNRS/IN2P3 (IJCLab, Orsay)

- Design was performed
- Several treatments have been tested on 2 prototypes
    - Optimal surface treatment procedure producing excellent performance defined
        - buffered chemical processing (BCP) + H degassing at 650°C during 10h without post chemical etching
    - Procedure optimal in performance, but also in simplicity : important for a series of 60 cavities
- First cavities in production



MYRRHA working point



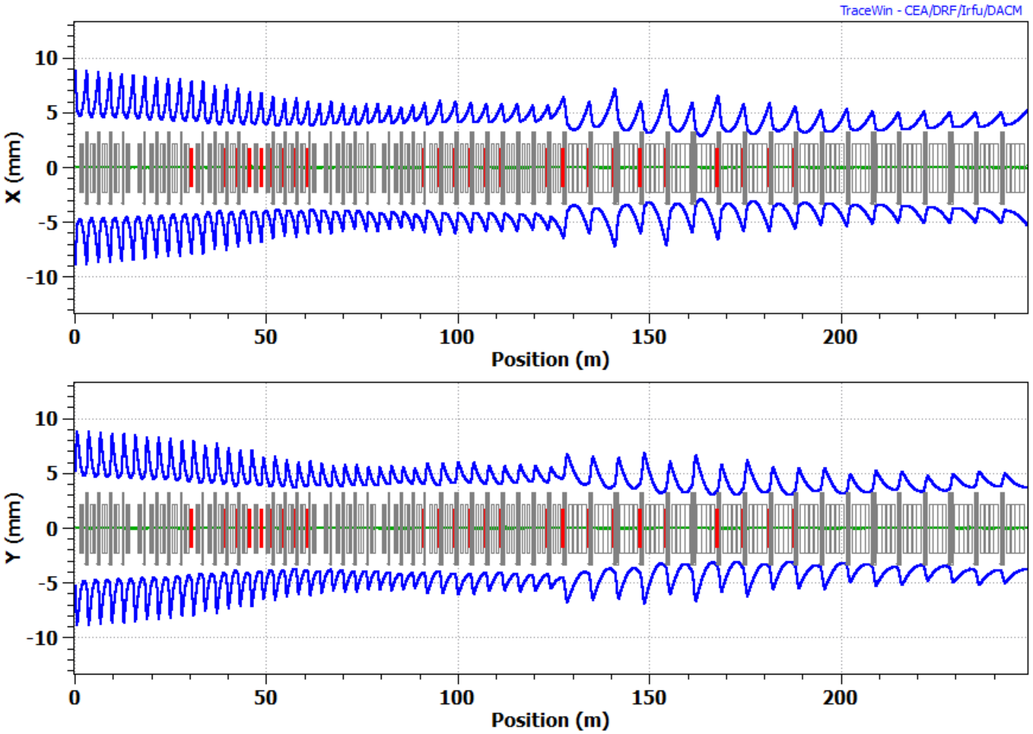
One of the best performance for this type of Spoke cavity in the world

H. Podlech, MYRTE final meeting, February 2019

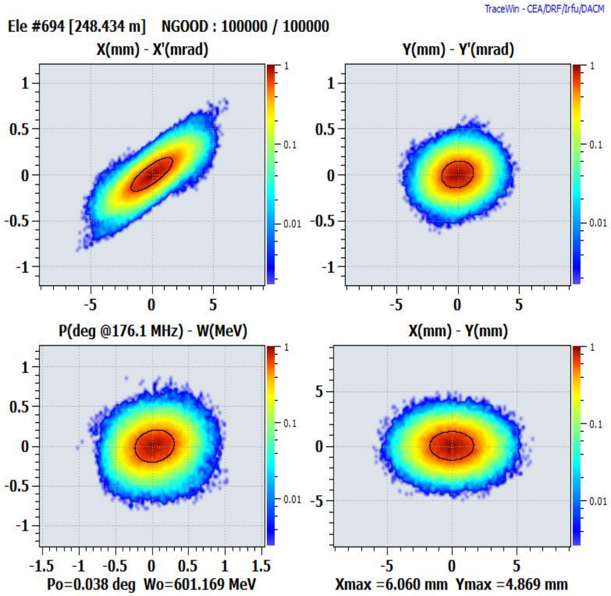
MYRRHA Research and Transmutation Endeavour

MYRRHA linac beam dynamics simulations

- ⟐ **Perform beam transport simulations on the whole linac to minimize emittance growth and beam loss under all possible operation**
  - Ensure global coherence of the 600 MeV linac design
  - Perform start-to-end beam simulations of the whole machine



Beam envelope throughout the 600 MeV linac



Emittance at 600 MeV

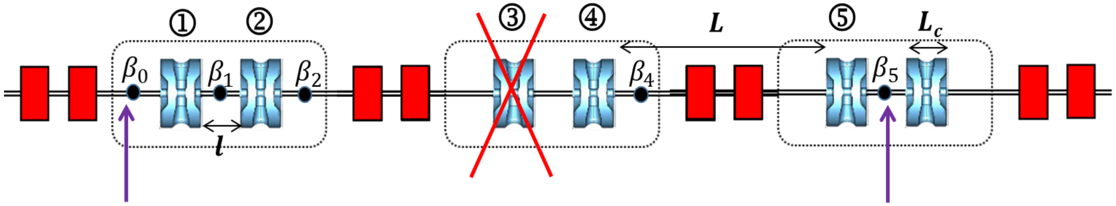
- ⟐ **Beam dynamics performed for the 100 MeV linac as well**

MYRRHA Research and Transmutation Endeavour

F. Bouly, MYRTE final meeting, February 2019

Method to implement fault recovery

- Recovery in case of a failure of an accelerating cavity



Beginning of the retuning area

End of the retuning area

- Goals of the method :
  - **Conserve energy and phase at the exit of the retuning area (maintain time of flight)**
  - Minimize variations of longitudinal transfer function
  - Minimize abrupt variations of phase advance

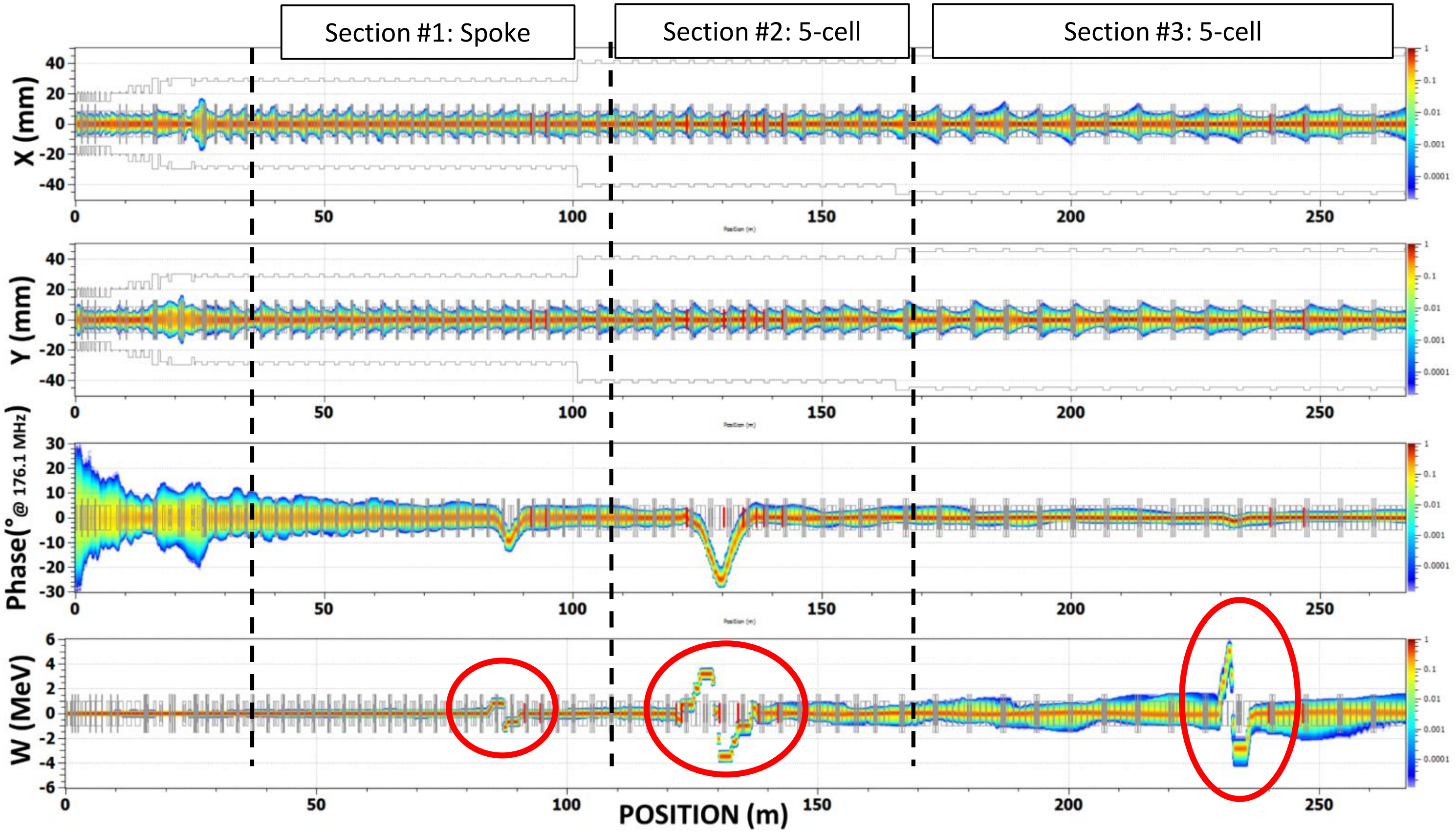
- Method
  - Fast calculation of new operating set points of neighbouring cavities to build a data base
  - Use « machine learning » to optimize the re-tuning algorithm

- Impact on the design of the control and tuning system of accelerating cavities
  - Modelling and simulations of the Low Level RF system (to ensure accuracy and speed)

F.Bouly, "The MYRRHA Superconducting linac Fault-tolerant design and developments", TCADS4 workshop, Antwerp, Belgium, October 2019

Feasibility studies of fault recovery

- Algorithm developed for algorithm for automatic retuning in case of multiple cavity failures
  - Example with 3 failures : Section #1: 1 Spoke cavity, Section #2: 1 Cryomodule (i.e. 2 cavities), Section #3: 1 Elliptical cavity



Beam envelope in scenario with 3 failures

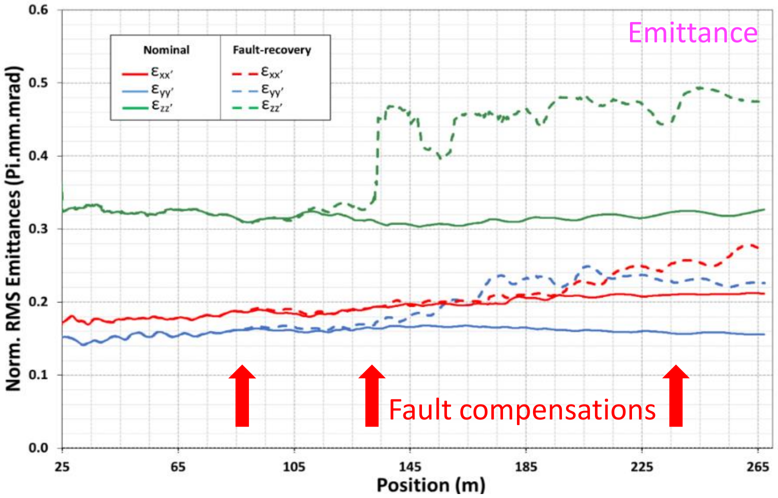
➔ Fault recovery algorithm successful

F. Bouly, séminaire thématique accélérateurs et instrumentation (GT07), Orsay, France , 2020

Feasibility studies of fault recovery

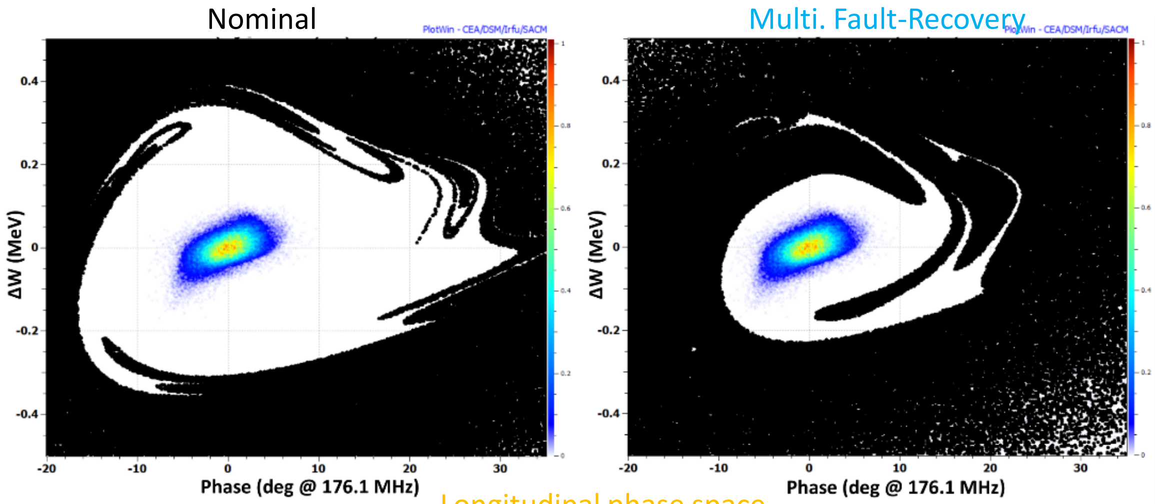
- Feasibility of beam retuning have been assessed

- Impact of fault compensation on beam dynamics
  - Losses (> 1W/m) can occur on a non perfect machine (statistical errors)
  - Fault compensation may induce
    - emittance growth
    - longitudinal acceptance decrease



Emittance

Fault compensations



Longitudinal phase space

➔ Further studies underway

F. Bouly, séminaire thématique accélérateurs et instrumentation (GT07), Orsay, France , 2020

5. CONCLUSIONS

Conclusions - 1/2

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

- Waste incineration & **ADS concept must be demonstrated at high power** (MYRRHA, Ci-ADS)

- Experimental program at low-power underway with GUINEVERE to define operational procedures and reactivity monitoring techniques of an ADS demonstrator

- Reference schemes of ADS demonstrators are based on a **~600 MeV, ~5 mA CW superconducting** proton LINAC

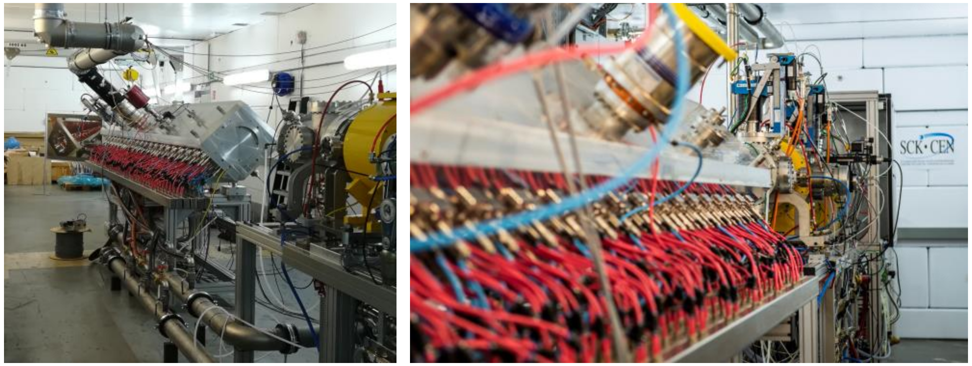
in the view of ADS at the industrial scale ~ 1GeV-1.3 GeV, 25-50 mA

Conclusions – 2/2

- R&D focused on **reliability issues** and fault recovery

- This R&D also brings substancial impact on the availability of high power proton linacs beyond the ADS community
  - LINAC4 runs an advanced tracking of faults to quickly improve its availability
  - SNS performs fault compensation using the best cavities at the end of the linac

- Construction of ADS demonstrators linacs has started with commissioning of injectors of MYRRHA and Ci-ADS



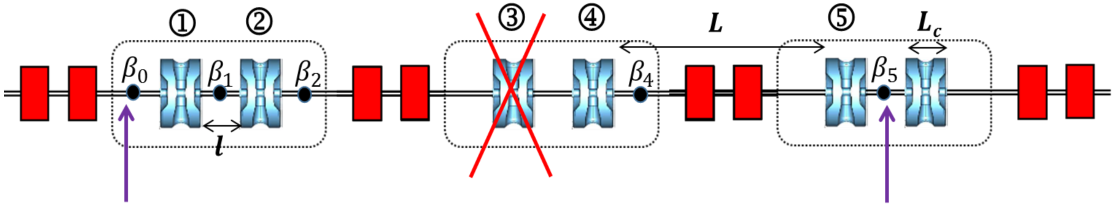
MYRRHA injector

Ci-ADS injector : CAFe

- ADS demonstration is on the way

THANKS FOR YOUR ATTENTION

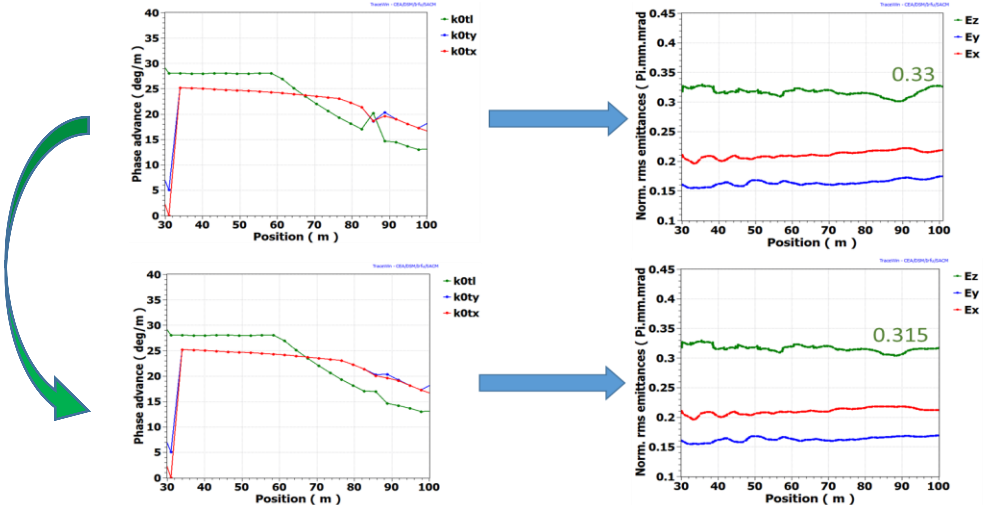
Axe 1 : Fault recovery – Algorithme dédié



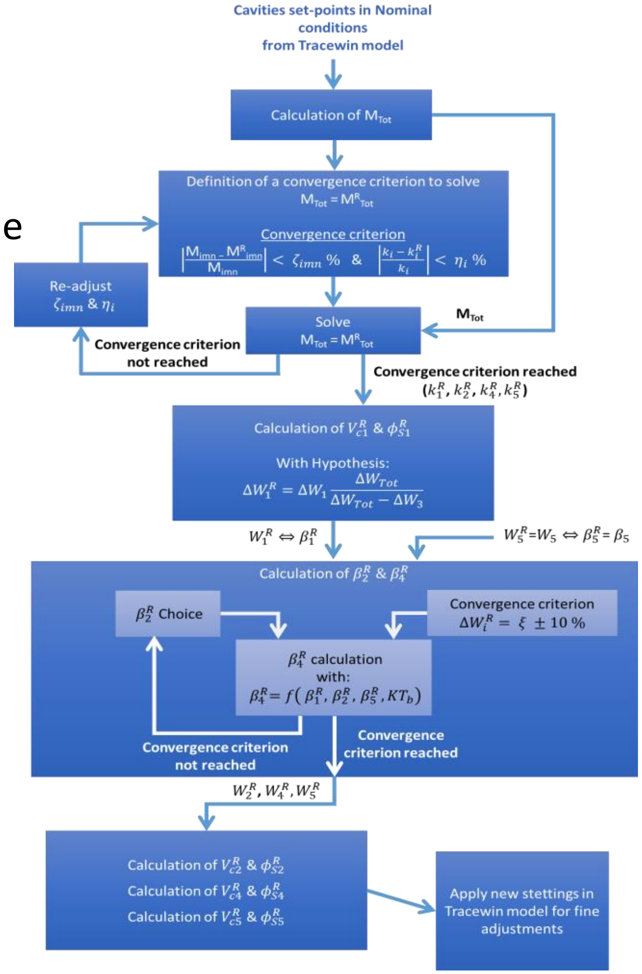
Beginning of the retuning area

End of the retuning area

- ⟐ Calcul rapide des nouveaux points de fonctionnement pour alimenter une base de données
- ⟐ Objectifs/Principes de la méthode:
  - ⟐ Retrouver la même énergie et la même phase en sortie de la 'zone de retuning'
  - ⟐ Minimiser les variation de la fonction de transfert longitudinale
  - ⟐ Minimiser les variation brusques d'avance de phase
- ⟐ Utiliser des méthodes de « machine learning » pour optimiser l'algorithme



Improvement with retuning method



Cavities set-points in Nominal conditions from Tracewin model

Calculation of M_{Tot}

Definition of a convergence criterion to solve $M_{Tot} = M^R_{Tot}$

Convergence criterion

$$\left|\frac{M_{imn} - M^R_{imn}}{M_{imn}}\right| < \zeta_{imn}\ \% \quad \& \quad \left|\frac{k_i - k_i^R}{k_i}\right| < \eta_i\ \%$$

Re-adjust ζ_{imn} & η_i

Solve $M_{Tot} = M^R_{Tot}$

M_{Tot}

Convergence criterion not reached

Convergence criterion reached $(k_1^R, k_2^R, k_4^R, k_5^R)$

Calculation of V_{c1}^R & ϕ_{S1}^R

With Hypothesis:

$$\Delta W_1^R = \Delta W_1 \frac{\Delta W_{Tot}}{\Delta W_{Tot} - \Delta W_3}$$

$W_1^R \Leftrightarrow \beta_1^R$

$W_5^R = W_5 \Leftrightarrow \beta_5^R = \beta_5$

Calculation of β_2^R & β_4^R

β_2^R Choice

Convergence criterion $\Delta W_i^R = \xi \pm 10\ \%$

β_4^R calculation with: $\beta_4^R = f(\beta_1^R, \beta_2^R, \beta_5^R, KT_b)$

Convergence criterion not reached

Convergence criterion reached

W_2^R, W_4^R, W_5^R

Calculation of V_{c2}^R & ϕ_{S2}^R
Calculation of V_{c4}^R & ϕ_{S4}^R
Calculation of V_{c5}^R & ϕ_{S5}^R

Apply new stettings in Tracewin model for fine adjustments

Proposed algorithm for cavities retuning calculations
F.Bouly, 2019