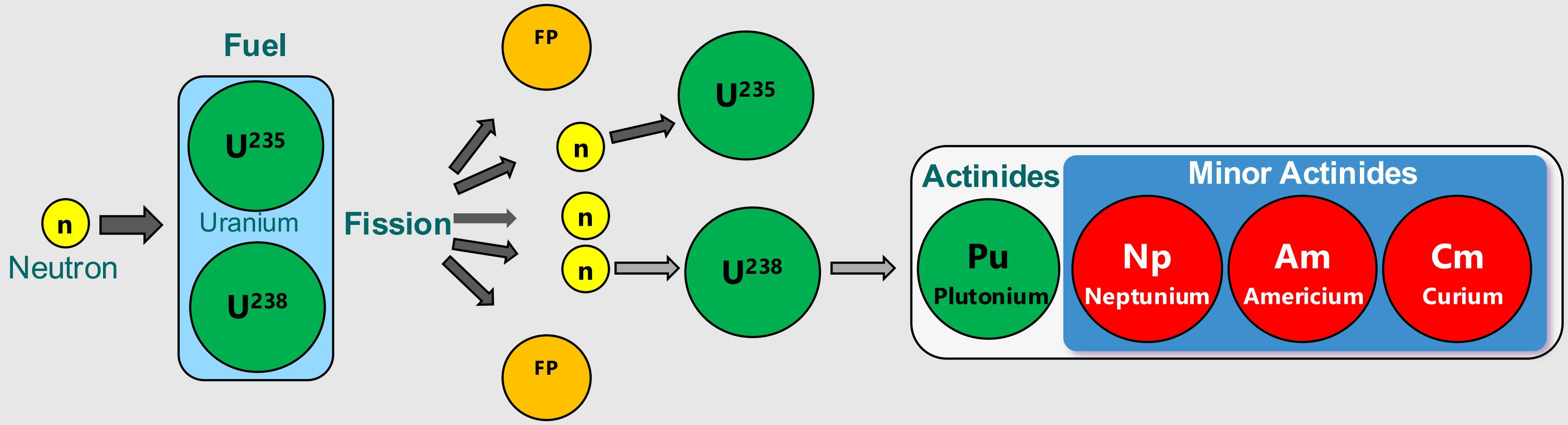
MYRRHA and its driver accelerator

Adrian Fabich on behalf of MYRRHA

sck cen
Belgian Nuclear Research Centre

NNV (astro-)particle physics – fall meeting, November 2025

Fission generates high-level radioactive waste

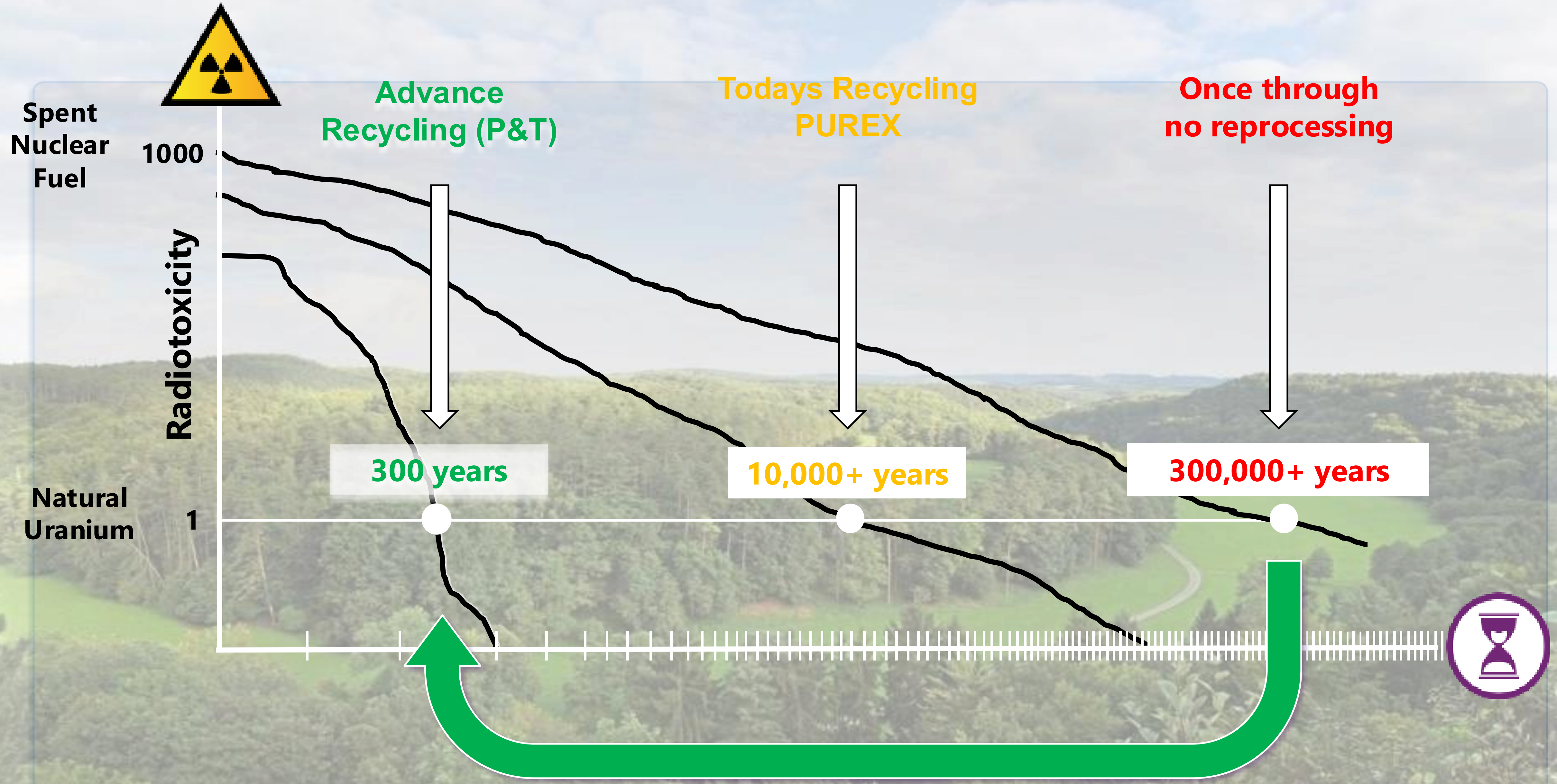


1 ton of nuclear fuel used 4,5 year in commercial PWR reactor **produces electricity for 100,000 Belgian families per year** (3500 kWh/y per family)

➔

After 4,5 years the spent nuclear fuel contains:

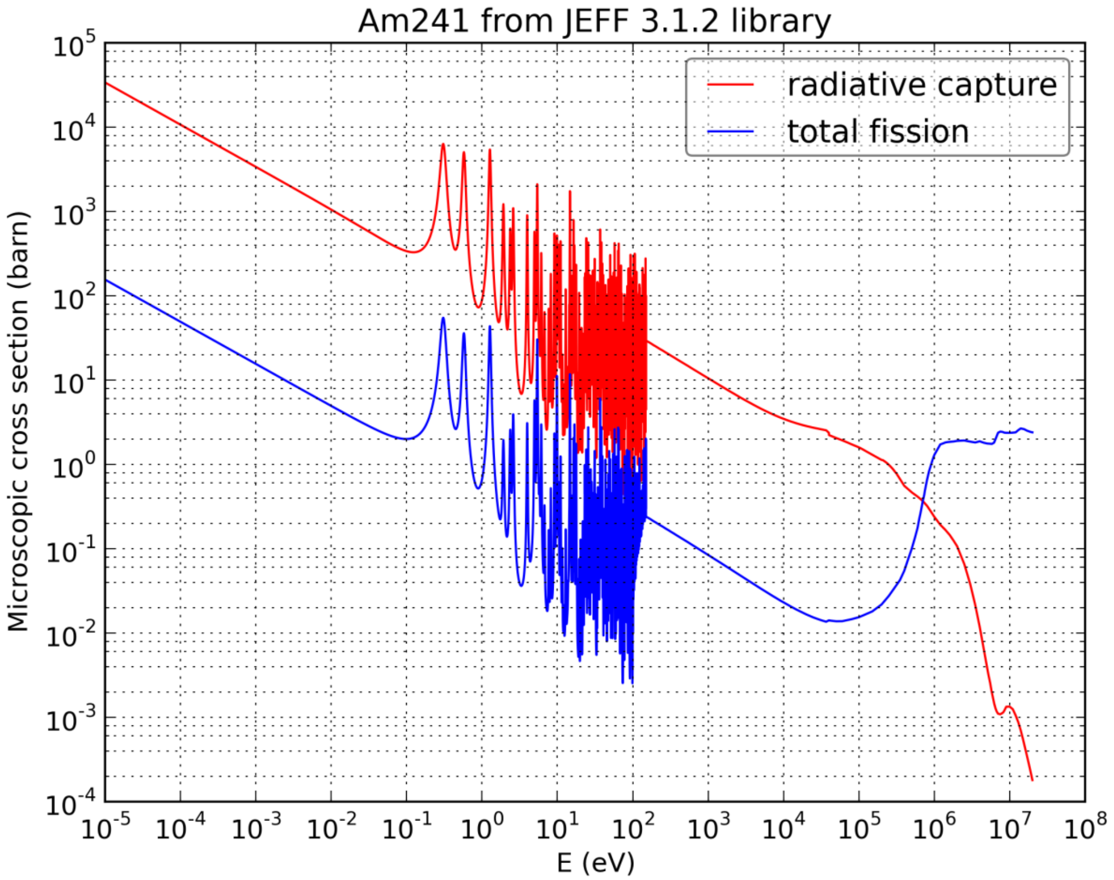
- **94,7% of resources we can recycle (U+Pu)**
- **5,1% of nuclear waste with low radiotoxicity (FP's)**
- **0,2% of high radiotoxicity nuclear waste**


Spent
Nuclear
Fuel
1000
Radiotoxicity
Natural
Uranium
1
Advance
Recycling (P&T)
Todays Recycling
PUREX
Once through
no reprocessing
300 years
10,000+ years
300,000+ years

Fast neutrons for transmutation

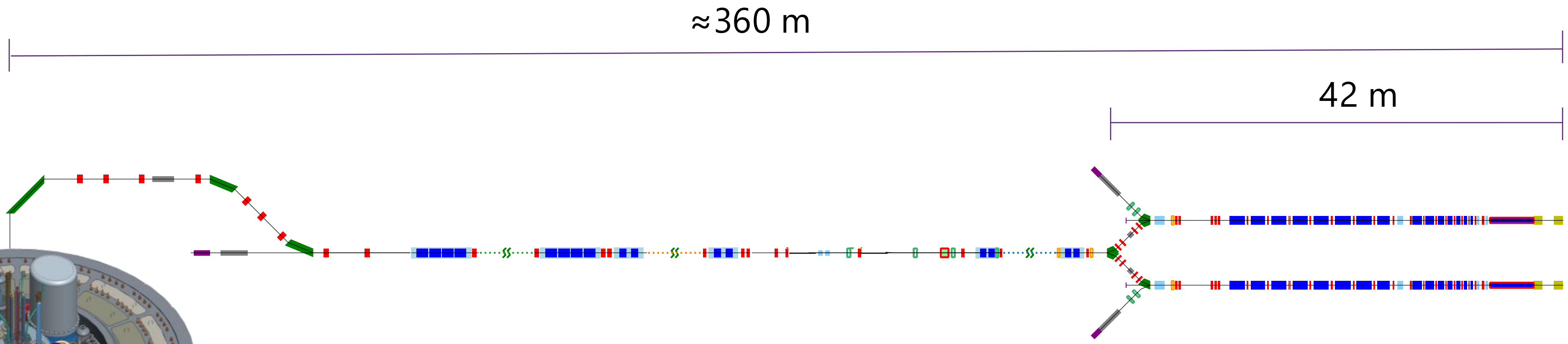
- Fission of minor actinides
- Resulting in radio-isotopes of lower radiotoxicity

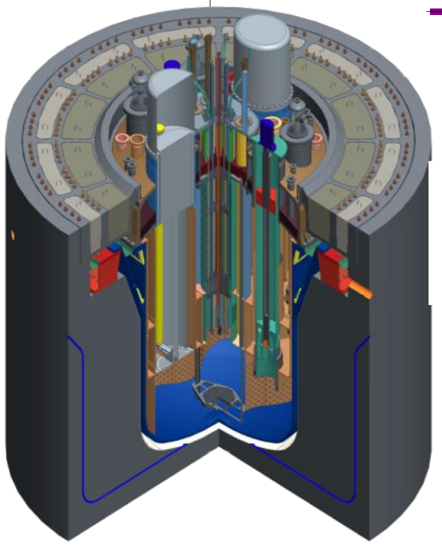
- Dominant cross-section for fission requires fast neutrons



Accelerator Driven System (ADS)

LINEAR ACCELERATOR
(600 MeV)





REACTOR

Sub-critical
Lead-Bismuth cooled

ADS reactor: rather a necessity than a virtue

- Both critical reactors and ADS can be used as transmutation systems
- Nevertheless, a big load of MAs can jeopardize the control of a critical reactor because of:

1) Reducing delayed neutron fractions, β (due also to the reduction of ^{238}U) and reduced margin to prompt criticality ($\rho = \beta$)

$$\psi(\mathbf{r},t) = \psi_o(\mathbf{r}) \sum_{m=0}^{M} A_m e^{\omega_m t} \qquad T = \frac{1}{\rho}\left[\frac{\ell}{K_{eff}} + \sum_{i=1}^{M} \frac{\beta_i}{\lambda_i}\right]$$

Characteristic period of the reactor

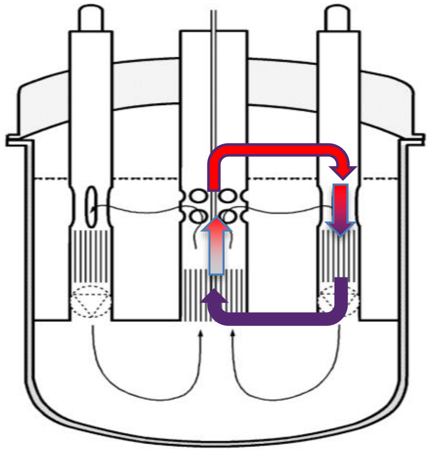
2) Doppler feedback reduced with increasing amount of MAs

The ADS can transmute big loads of MAs without losing safety and this solution is needed for heavily MA loaded core (>10%)

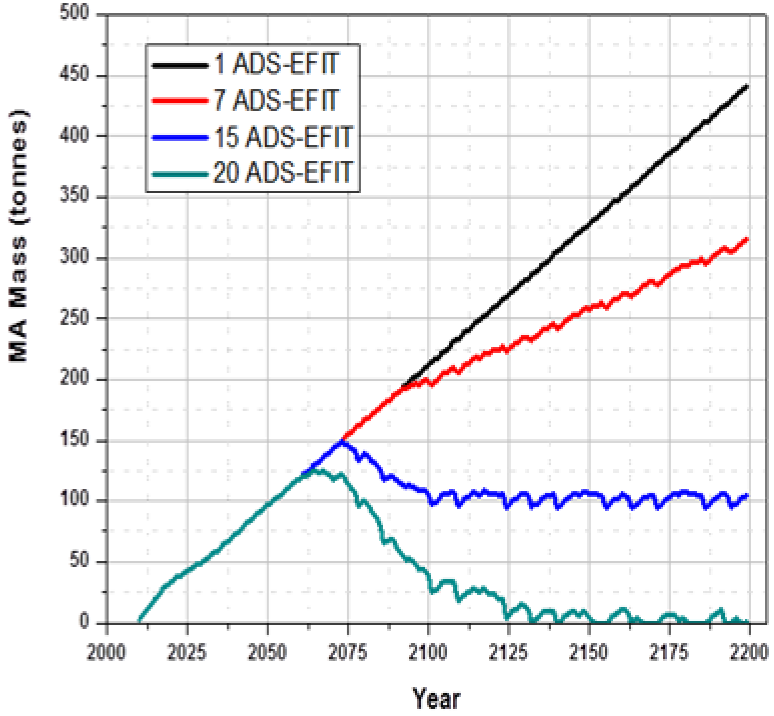
ADS inherent safety – by design principles

- Subcritical operation
- Nuclear ~~chain~~ reaction sustained by the accelerator beam power: the accelerator stops, the reactor 'stops'.
- In case required, turning off the accelerator (beam) immediately puts the reactor in a safe state as the nuclear reaction dies out.

- Remaining ADS heating power significantly lower than in conventional FR
- Sufficient self-cooling can be designed, based on natural circulation of the coolant by gravity between the cold Heat Exchanger (HX) and the hot core



Shared & efficient solution for Minor Actinides management
EU case with 144 power reactors using EFIT 400 MWth



→ 15 EFIT with each 400 MWth required for all EU HLW treatment

Doel (BE) = 9000 MWth
Tihange (BE) = 9000 MWth

Core safety parameters limit the amount of MA that can be loaded in the critical core for transmutation. Possible transmutation rates:

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

EFIT = European Facility for Industrial-Scale Transmutation

MYRRHA

7 September 2018

The **Belgian Federal Government** announce its **decision to**:

- **Build MYRRHA**, a new large research infrastructure in Mol
- Establish **governmental support** for promoting MYRRHA **international partnership**
- Establish the **MYRRHA international not-for-profit organization** (Founded in 2022)

MYRRHA AISBL: separate legal entity to welcome external partners/investors

MYRRHA
sck cen

MYRRHA International non-profit organisation

Responsibility:

SCK CEN

- Design & build MINERVA
- Conduct R&D for phases 2 ACC-600 & 3 MYRRHA Reactor
- Obtain licenses for Phase 1 and later on for Phases 2 & 3
- <u>Being the nuclear operator</u> of MYRRHA/MINERVA

MYRRHA

- Establish the MYRRHA International Consortium
- Guarding the overall scope of MYRRHA program
- Receiving & managing funds for the realization of MYRRHA/MINERVA

SCK CEN

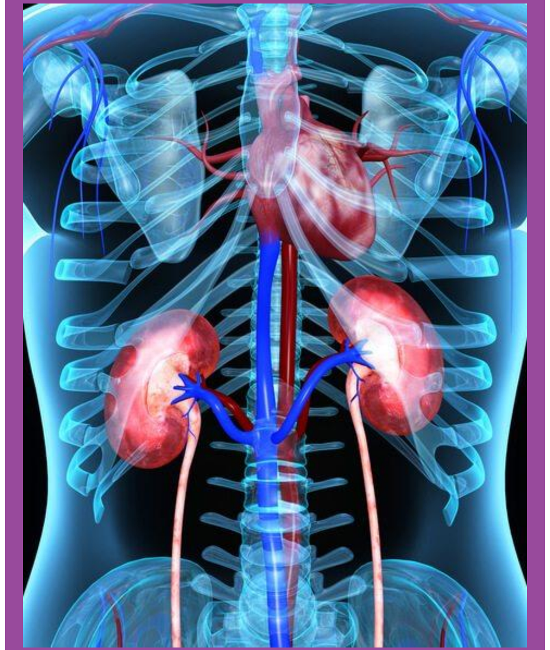
- The Belgian Institute for Nuclear Research
- Founded in 1952
- ≈ 950 employees, ≈250 MEuro annual budget
- Reactors for
  - 1/3 of worldwide radio-pharmaceuticals
  - High power semiconductor doping
  - Calibration
  - One just completed dismantling (BR1)
  - One “tiny” one already coupled to a 30keV accelerator (zero-power ADS)
  - ...
- ≈ 2 hours drive from Utrecht

ADS demonstrator - MYRRHA's versatility

Less (toxic) nuclear waste

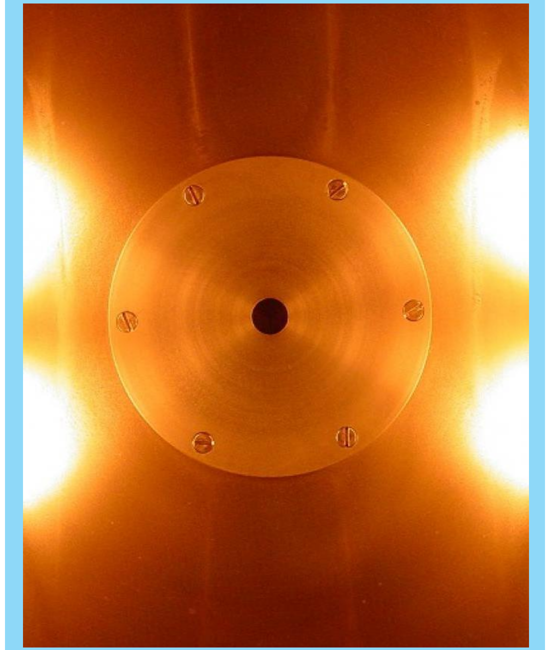
Transmutation reduces the final residual waste **volume** by a **factor 100 and natural radiation level** is reached after **300 years**

Production of medical radio-isotopes



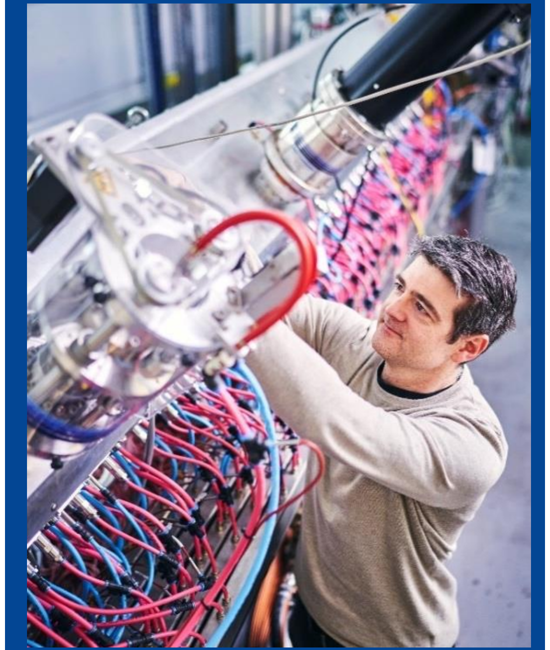
Therapeutic radio-isotopes can **fight cancer cells** in a more targeted way with significant **reduction of side effects for patient**

New reactor concepts



A wide range of material testing by **fast neutrons** for development of **fusion reactors** as well as used in current **fission reactors**

Fundamental research



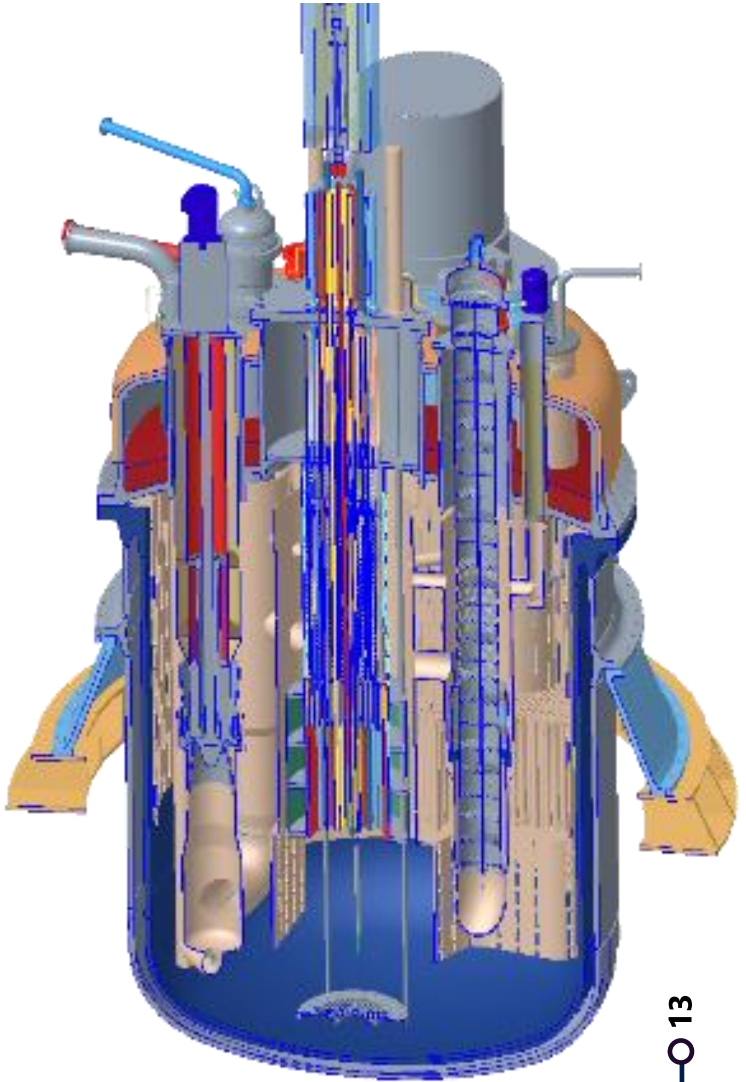
Deepening understandings in **Nuclear physics**, **atomic physics**, **fundamental interactions**, **solid state physics** & **nuclear medicine**

MYRRHA reactor

- Conceptual design phase completed
- Commissioning from second half of 2030s

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

- Integrated Pool-type concept with LBE coolant
- Fuel assemblies: hexagonal bundles of cylindrical wire-spaced fuel pins (MOX fuel 30wt.% Pu)
- 4x heat exchangers: double-walled with leak detection; water/steam on secondary side
- Bottom core loading: single in-vessel fuel handling machine (IVFHM)

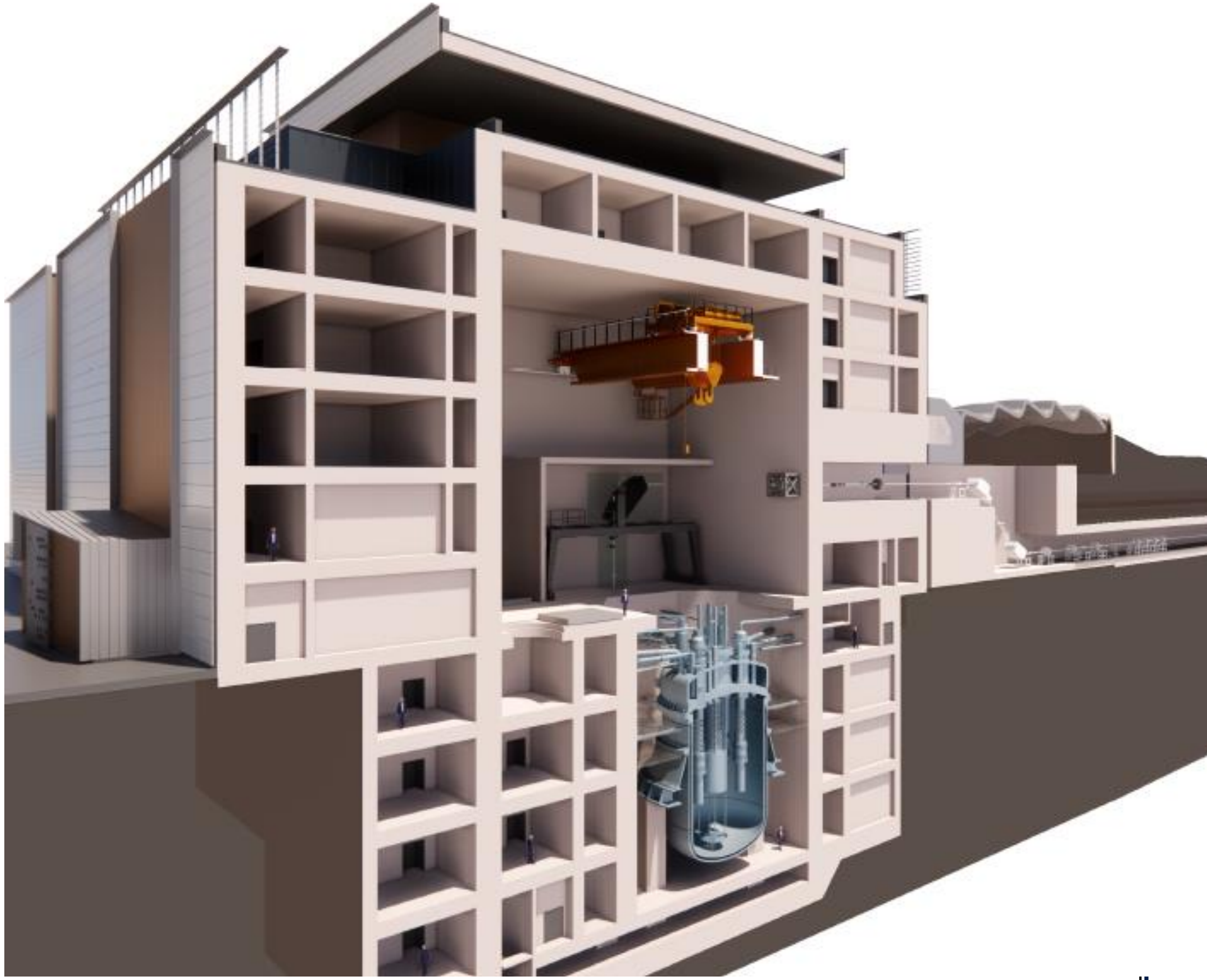


N.B.: similar design (liquid lead fast reactor) can also be used for energy production

- 'Energy amplifier' introduced by Carlo Rubbia in the 1990s

MYRRHA Reactor Buildings

- Multi-disciplinary integration
  - Reactor Building
    - Nuclear material handling
    - Ex-vessel remote handling
    - Hot Cells
    - Building Equipment
    - HVAC
    - Utilities
      - Process
      - I&C
      - Electrical
      - Fire protection
  - Accelerator
  - Spent Fuel Building
  - Waste Building



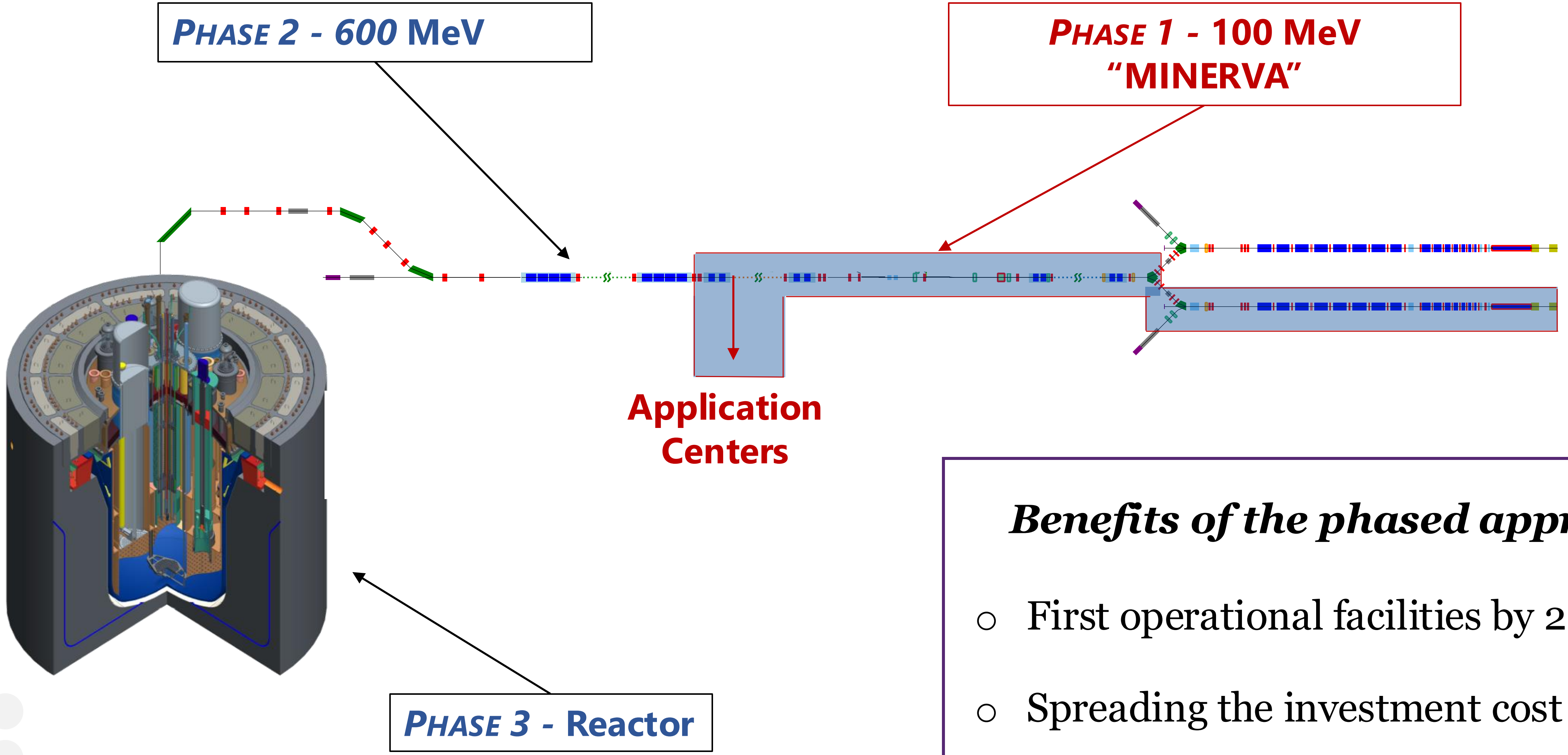
MYRRHA Facilities
for R&D support for Design & Safety







MYRRHA, *a phased approach*



Benefits of the phased approach

- First operational facilities by 2030
- Spreading the investment cost

MYRRHA Licensing status: where are we?

- ***MYRRHA Phase 1: MINERVA Licensing***
  - License for construction & operation for the class IIA MINERVA installation obtained in November 2022
  - Preparation of testing plan and list of HP&WPs for phased construction & commissioning of nuclear safety relevant structures, systems and components (2024-2027)
- ***MYRRHA Phase 3: Reactor Pre-licensing***
  - End 2024 the pre-licensing was finalized
  - FANC issued the final report to the Belgian Government, on the licensability of the MYRRHA reactor.
- *MYRRHA Phase 2: Extension of the Accelerator to 600 MeV*
  - Extension of the MINERVA license conditional to the opinion of the Belgian Government on the reactor licensability

ACCelerator requirements

- Protons
- > 600 MeV
- MW class average beam power
  - mA CW beam current
  - duty factor adaptation
- Reactor cycle operational schedule
  - MYRRHA: 90 day cycle
  - industrial ADS: quasi continuous

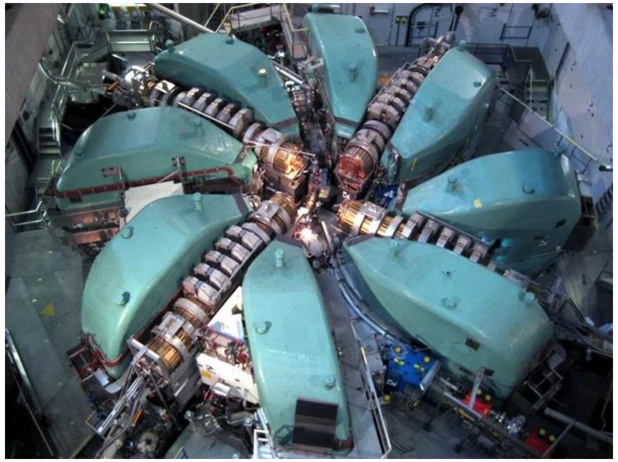
- High reliability
  - no beam interruption > few s
  - to avoid thermal stress on reactor components
- High availability
  - To get uptime
- Cost/Energy efficiency (CAPEX/OPEX)
  - Industrial approach

Options & worldwide efforts

- SC-Linac:
  - **MYRRHA – 1st stage (100 MeV) in implementation**
  - **CiADS – in implementation**
  - JADS – design study
  - …
- Cyclotron
  - Transmutex company – design study
  - TEXAS A&M university – design study for stacked cyclotrons
  - ….

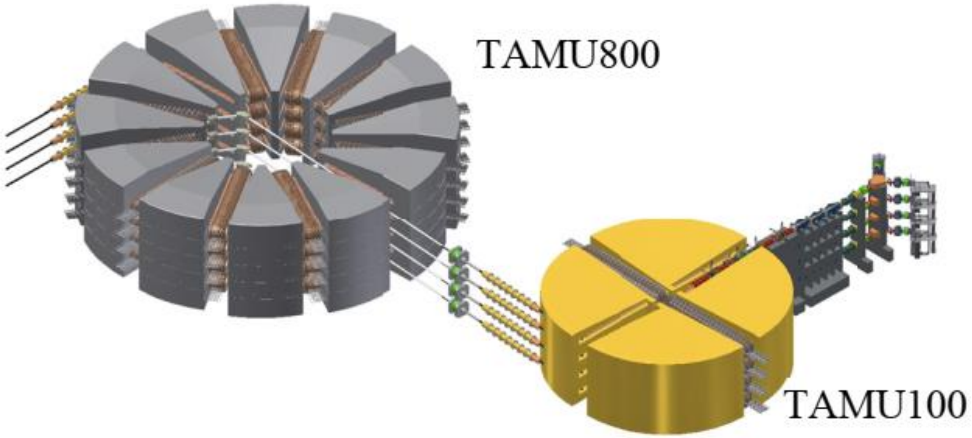
Option 1: Cylotrons

- Existing cyclotrons reach MW
- Several design studies

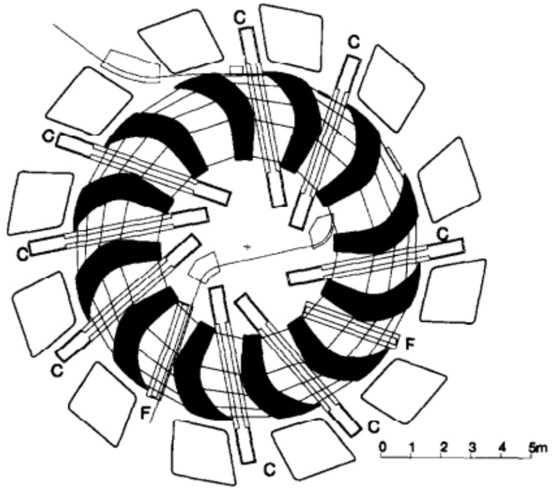


psi.ch

transmutex.com



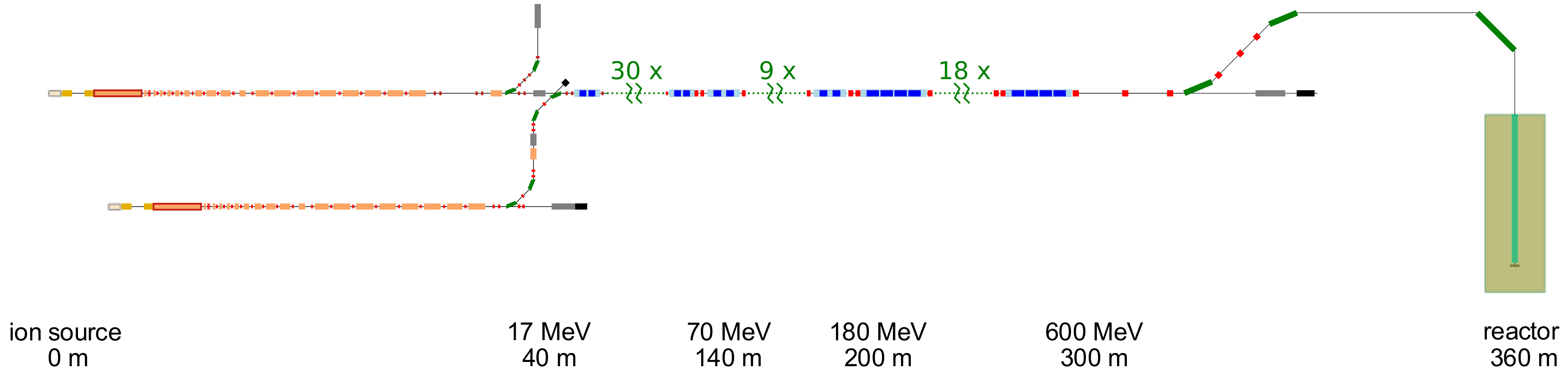
A. Sattarov et al, IPAC'2012



Th. Stammbach, "Proposal for 10MW cyclotron"

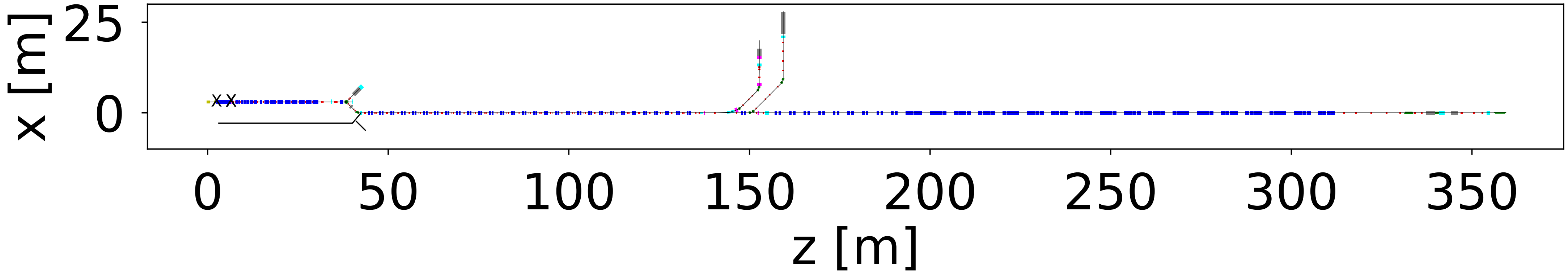
Option 2: Superconducting linacs

- CiADS – in implementation
- MYRRHA – 1st stage (100 MeV) in implementation
- Multiple design studies

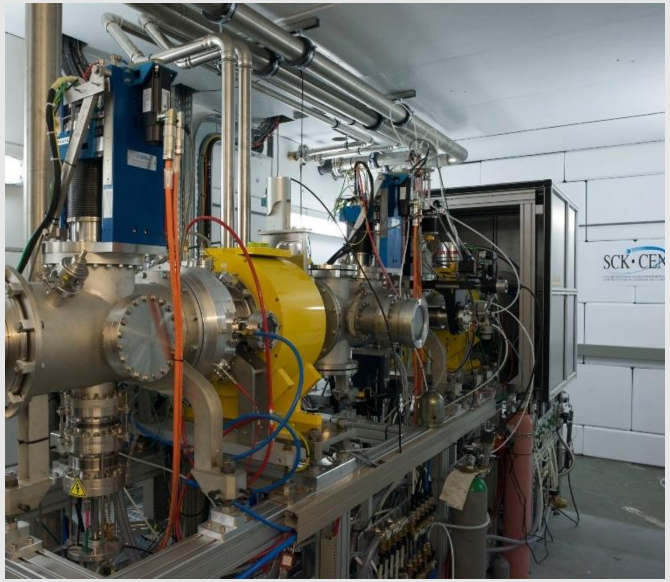


MYRRHA - accelerator key design decisions

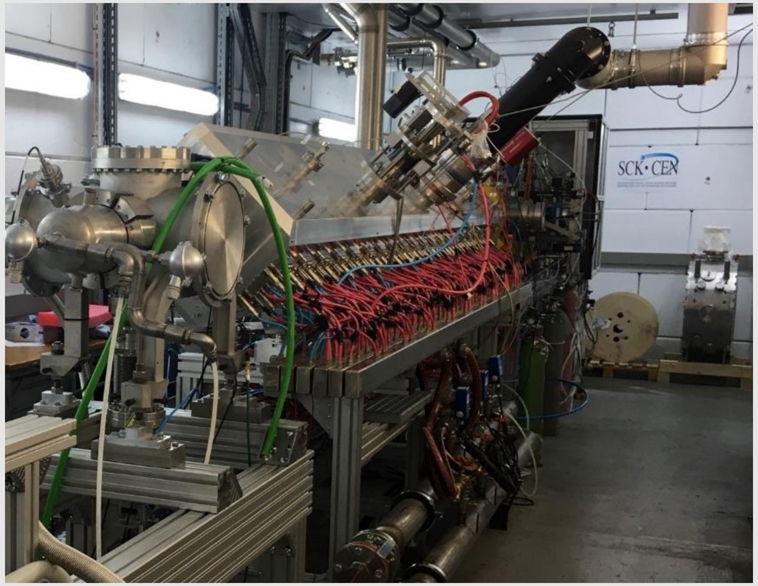
- 17 MeV normal conducting injector
  - Parallel redundancy
- Superconducting linac (100/600 MeV)
  - 3 types of SC cavities, operated at 2K
  - Significant RF-power overhead for serial redundancy/availability
- Use of solid state amplifiers



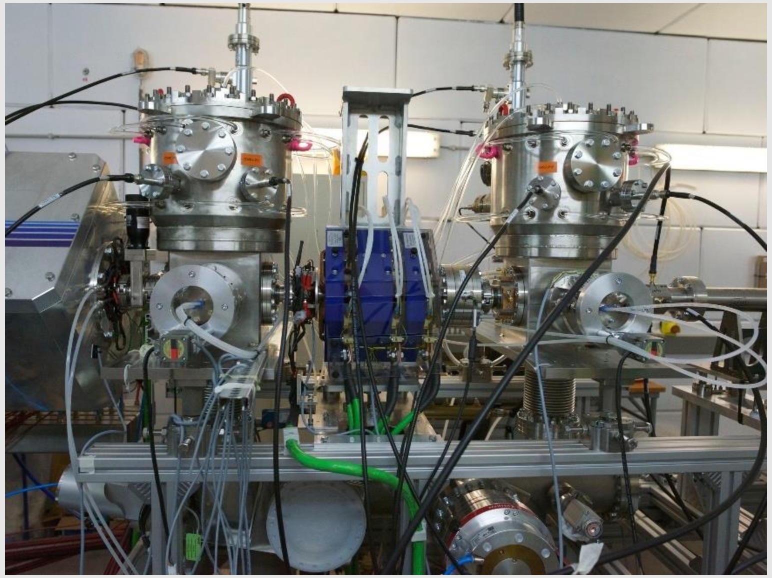
Injector front-end



Pantechnik Monogan1000
LEBT
- 2 solenoids optics
- gas injection for SCC
- 2 Allison emittancemeters
- electrostatic chopper
- ACCT



4 rod RFQ
up to 160kW

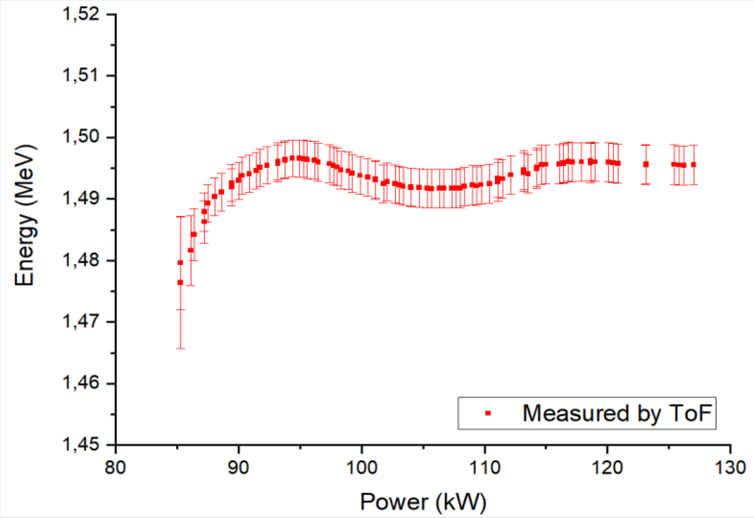


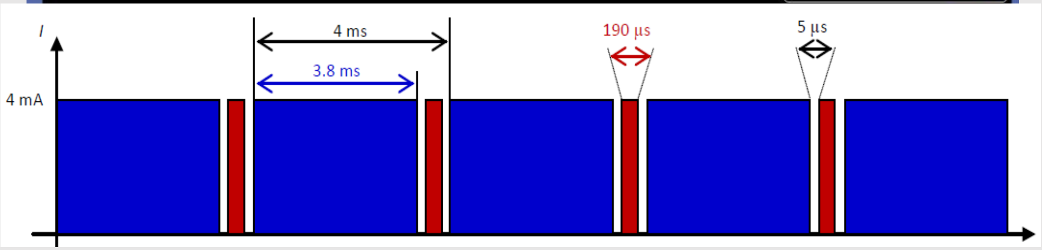
Rebunching section

Injector front-end commissioned

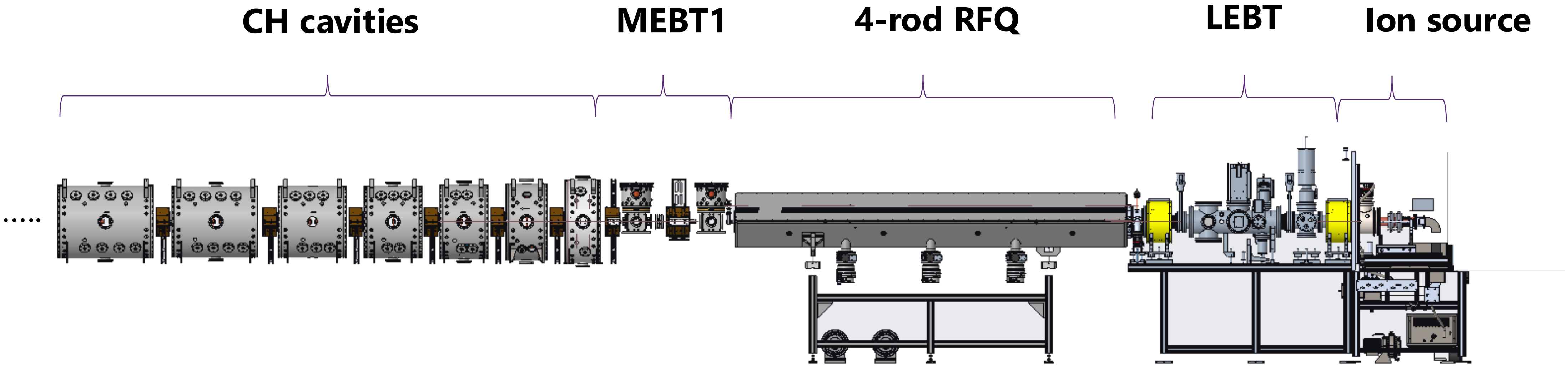
RFQ commissioned with 95% transmission in nominal conditions

- ***Nominal energy : 1.494 ± 0.003 MeV***





17 MeV Injector



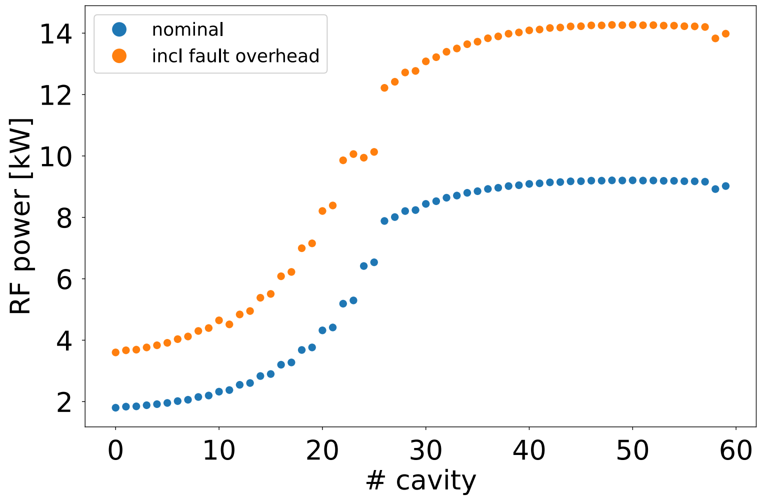
176 MHz normal conducting RF
- 4-rod RFQ with up to 160 kW to 1.5 MeV
- 2 Quarter-wave resonators
- 15 accelerating + 2 rebunching CH-cavities
- RFQ & Cavity design by IAP/Bevatech
- CH-cavity production started at RI

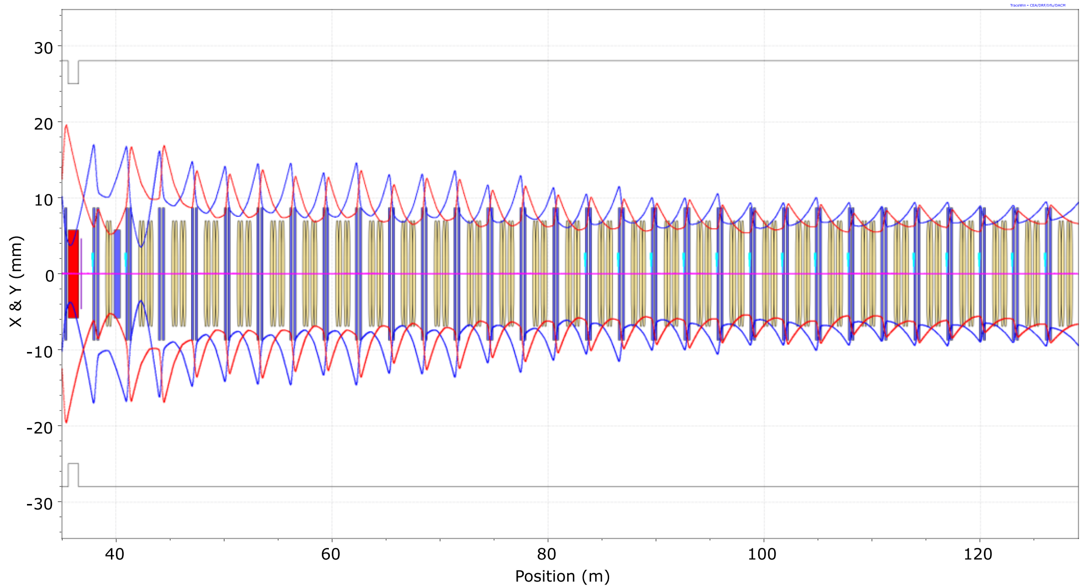
30 keV ECR-DC-proton source (Pantechnik)

LEBT: 2 solenoids, chopper & BD

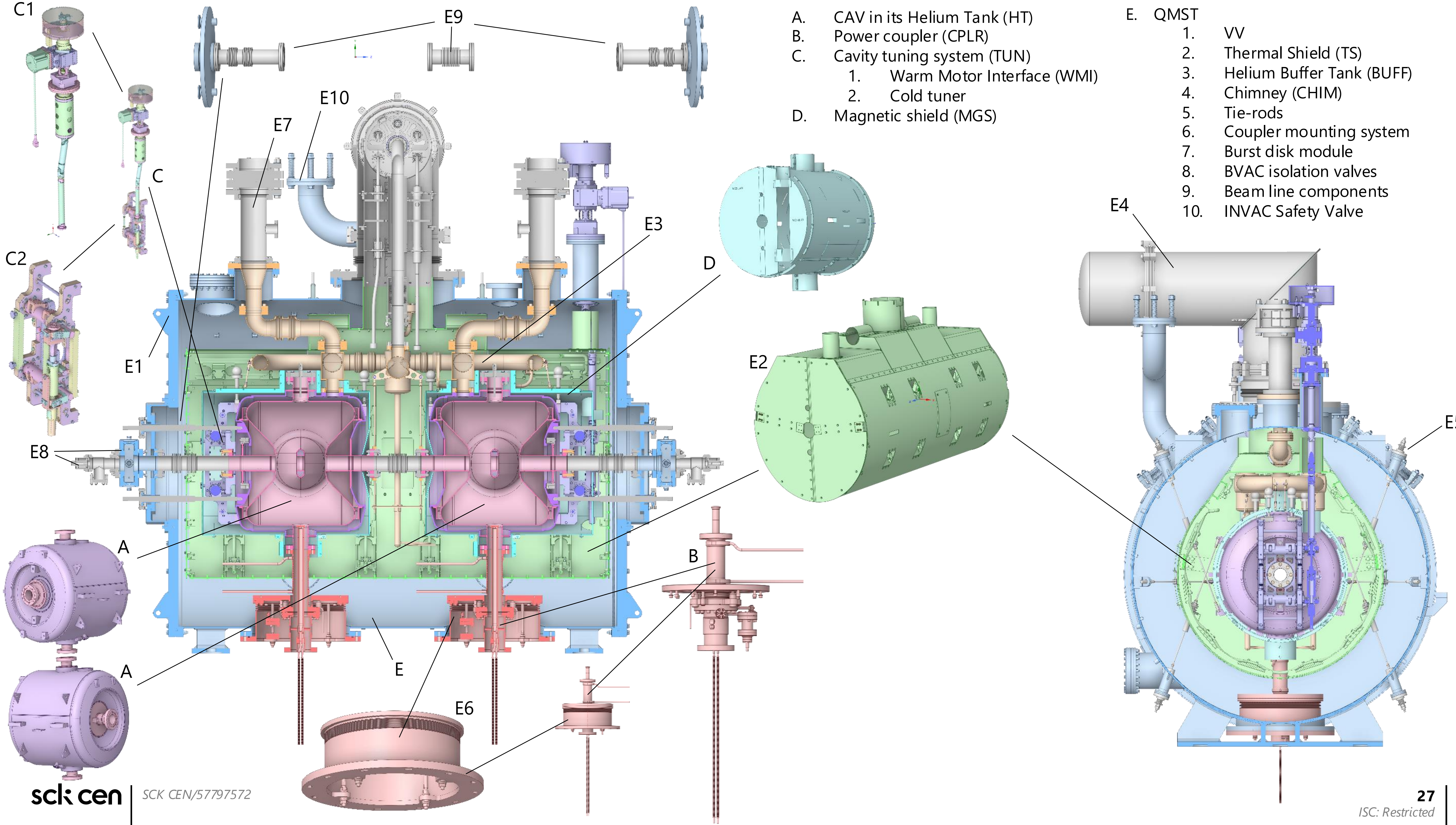
Super-conducting (SC) linac

- Optics & layout "classic high-power SC-linac-style":
  - 30 cryo modules with each 2 single spoke cavities (352.2 MHz, β = 0.352)
  - Warm section with doublet & diagnostic
  - BPM & correctors integrated into quadrupoles
- Last doublet used to match into "HEBT"
- Significant RF-overhead for serial fault tolerance
- Matching optimization still ongoing

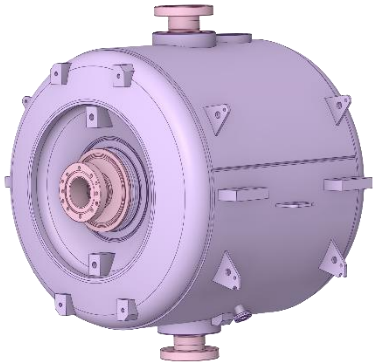




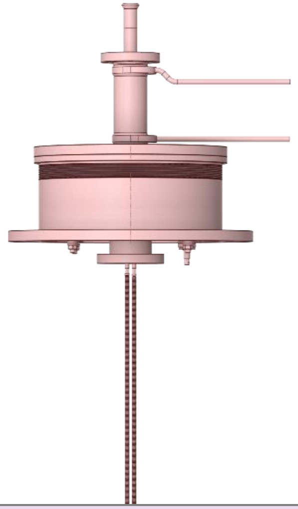
A. CAV in its Helium Tank (HT)
B. Power coupler (CPLR)
C. Cavity tuning system (TUN)
   1. Warm Motor Interface (WMI)
   2. Cold tuner
D. Magnetic shield (MGS)
E. QMST
   1. VV
   2. Thermal Shield (TS)
   3. Helium Buffer Tank (BUFF)
   4. Chimney (CHIM)
   5. Tie-rods
   6. Coupler mounting system
   7. Burst disk module
   8. BVAC isolation valves
   9. Beam line components
   10. INVAC Safety Valve



Cryomodule components

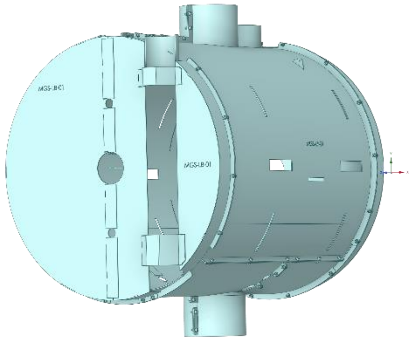


CAVity

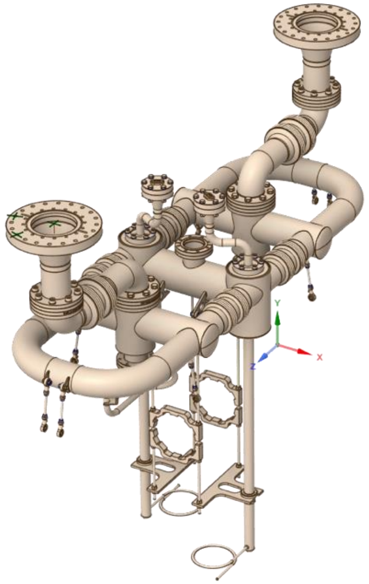


CPLR – RF coupler

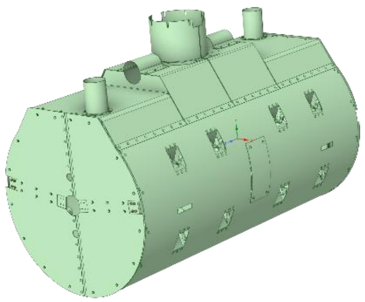
TUNer



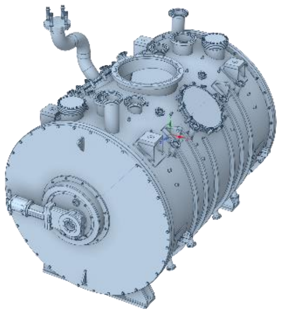
MGS - magnetic shield



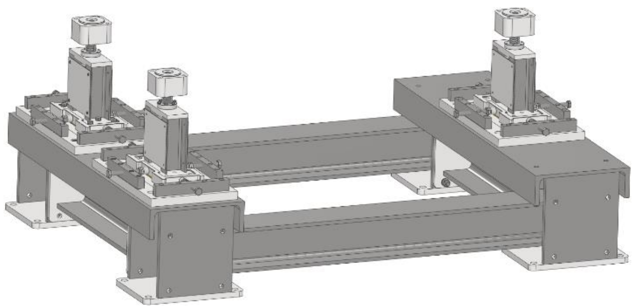
Helium BUFFer



TS –thermal shield



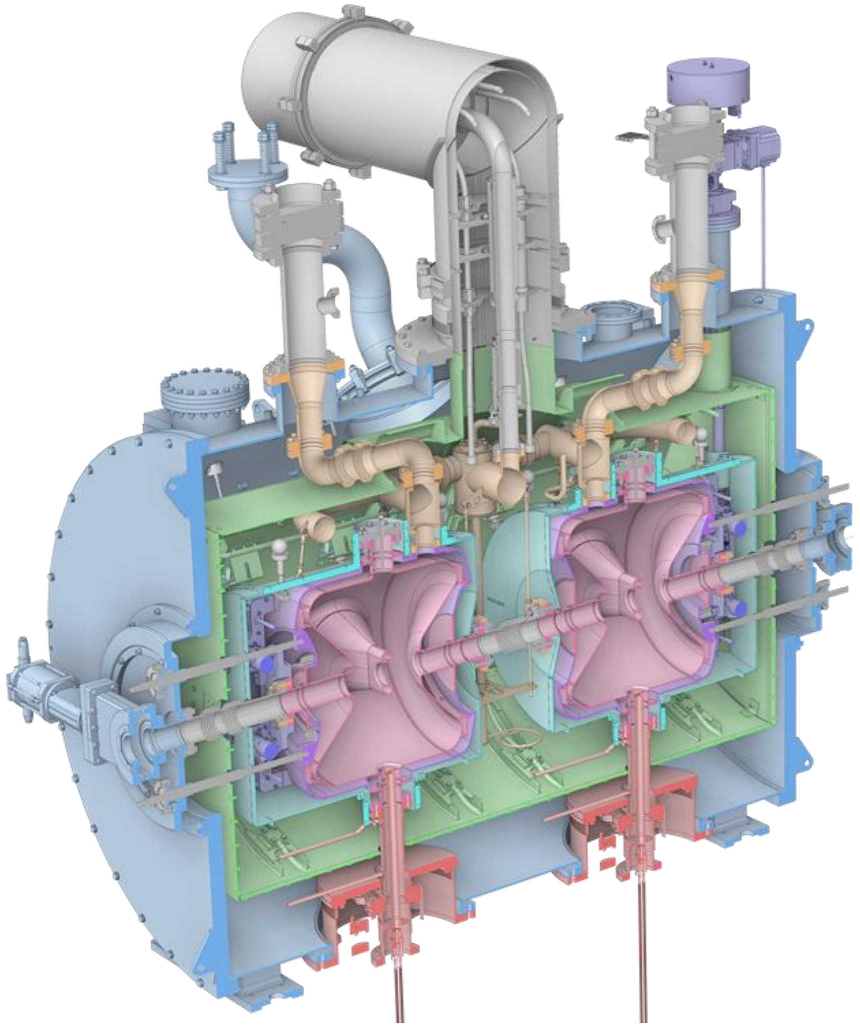
QMST –cryostat vessel



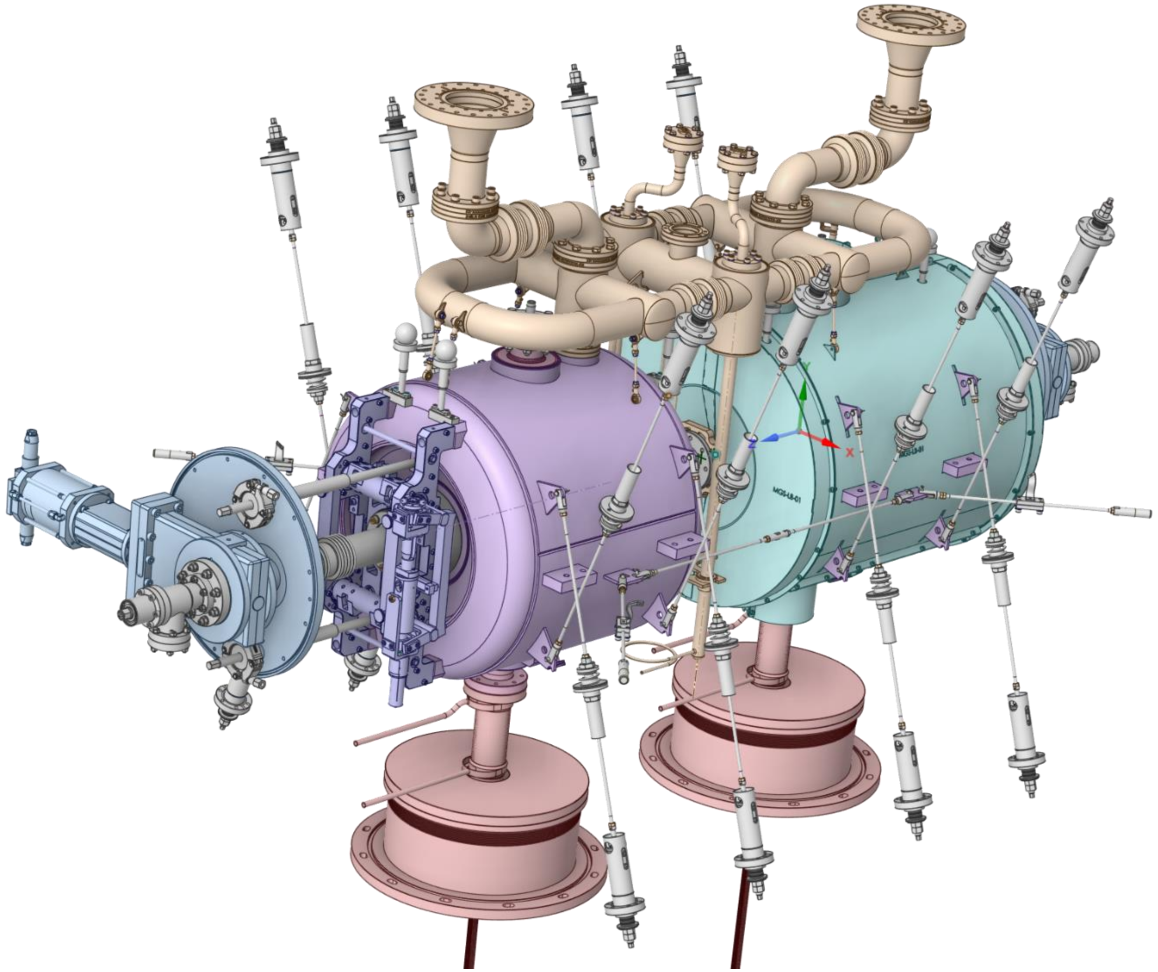
Support

Cryomodule

Cross section



Internal Components



Reliability in MYRRHA accelerator

- Design choices
  - Linear accelerator
  - Injector: parallel redundancy
  - SC linac: serial redundancy

    installing RF overhead

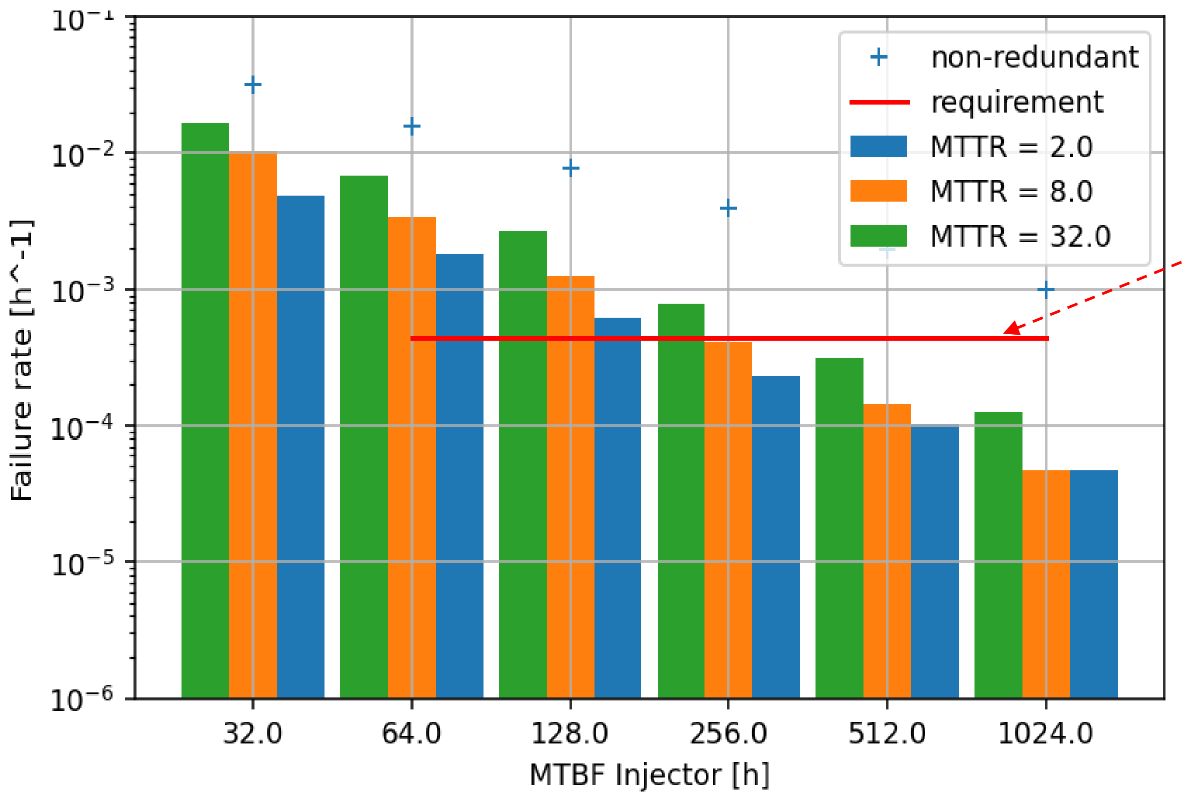
    Fast de-tuning of SC cavities

- Reliability model
  - in collaboration with CERN
  - using AvailSim4

Injector reliability - AVAILSIM4 simulations

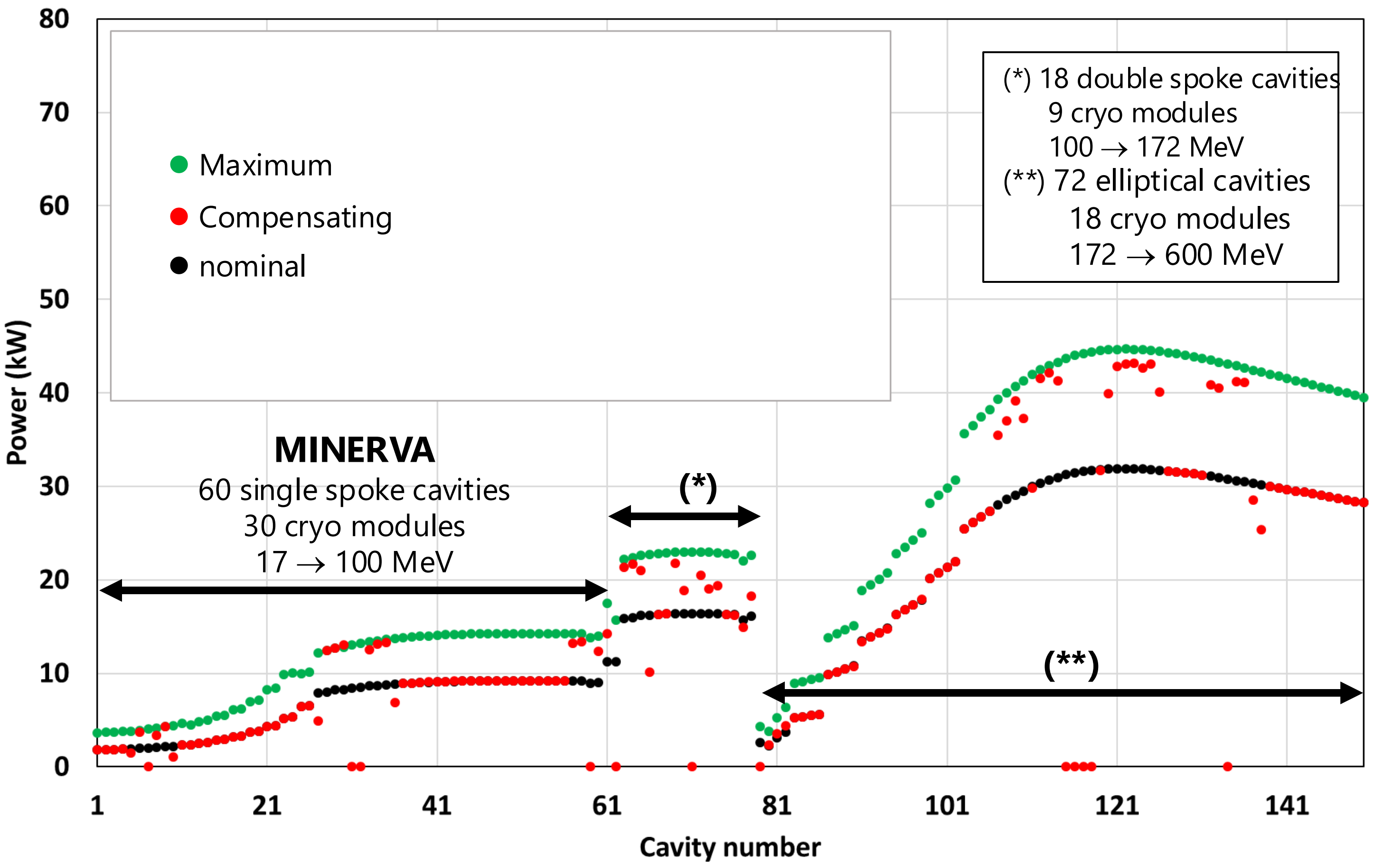
✓ Availability of the linac simulated with Monte Carlo code (AVAILSIM4)

✓ AVAILSIM4 result for the redundant injector strategy:



- target failure rate per hour for the injector deduced from breakdown of estimated individual failure rates for all components
- Failure rate/h simulated for
  - different Mean Time Between Failures (MTBF)
  - different Mean Time To Repair (MTTR)

SC-LINAC: Dynamic RF-compensation



✓ The plot shows power requirements for all cavities from a pure beam dynamics point of view, when 4 neighboring cavities compensate 1 faulty cavity

QM supply chain

Cavity **[CAV]**

Coupler **[CPLR]**

Tuner System **[TUN]**

Magnetic Shield **[MGS]**

Cryostat **[QMST]**

5x manufacturing tenders

QM-assembly tender

Cryomodule **[QM]**

Assembly tender

Contractor

QM Prequalification at FREIA

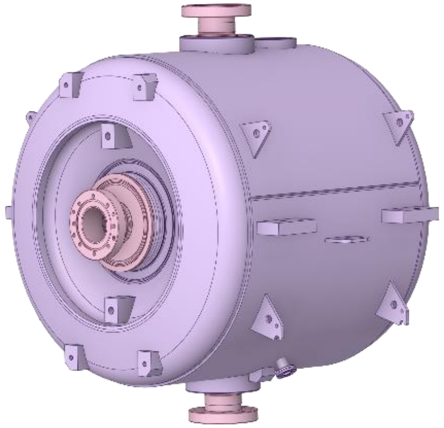
Cryomodule **[QM]**

Collaboration activity

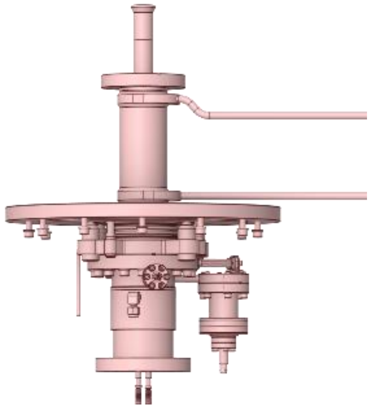
Collaboration

Installation

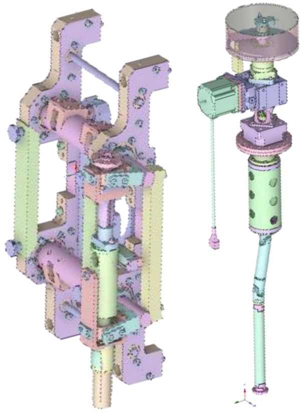
Internal activity



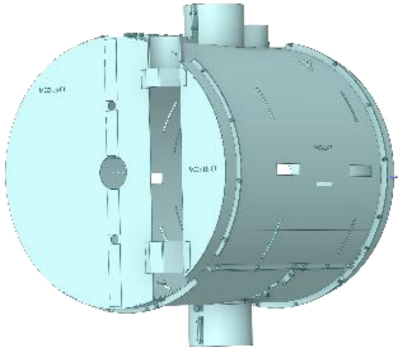
CAV Contractor



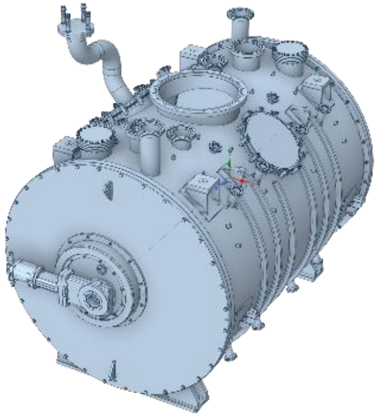
CPLR Contractor



TUN Contractor *To be awarded*



MGS Contractor



QMST Contractor *To be awarded*

CE construction

- Started in 2024
- 2027 rain/wind tight

From 2027
- installation of general infrastructure

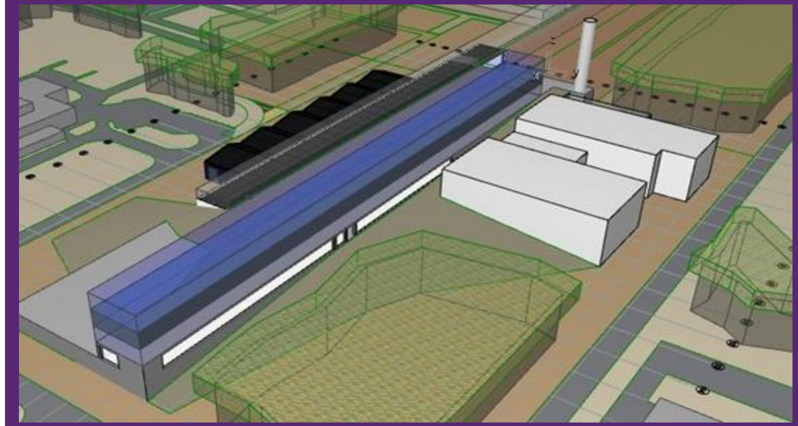
From 2028
- Accelerator installation

Timeline – phase 1

Nuclear licensing: approval received from authorities

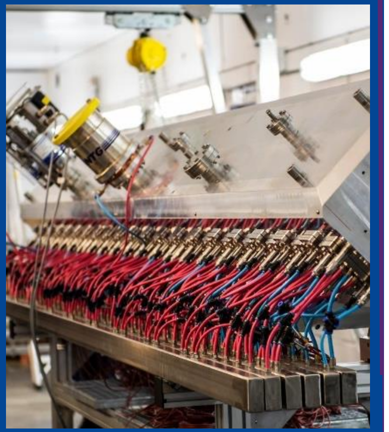
2016 | 2020 | 11/2022 | 2024 | 2028 | 2030

Design



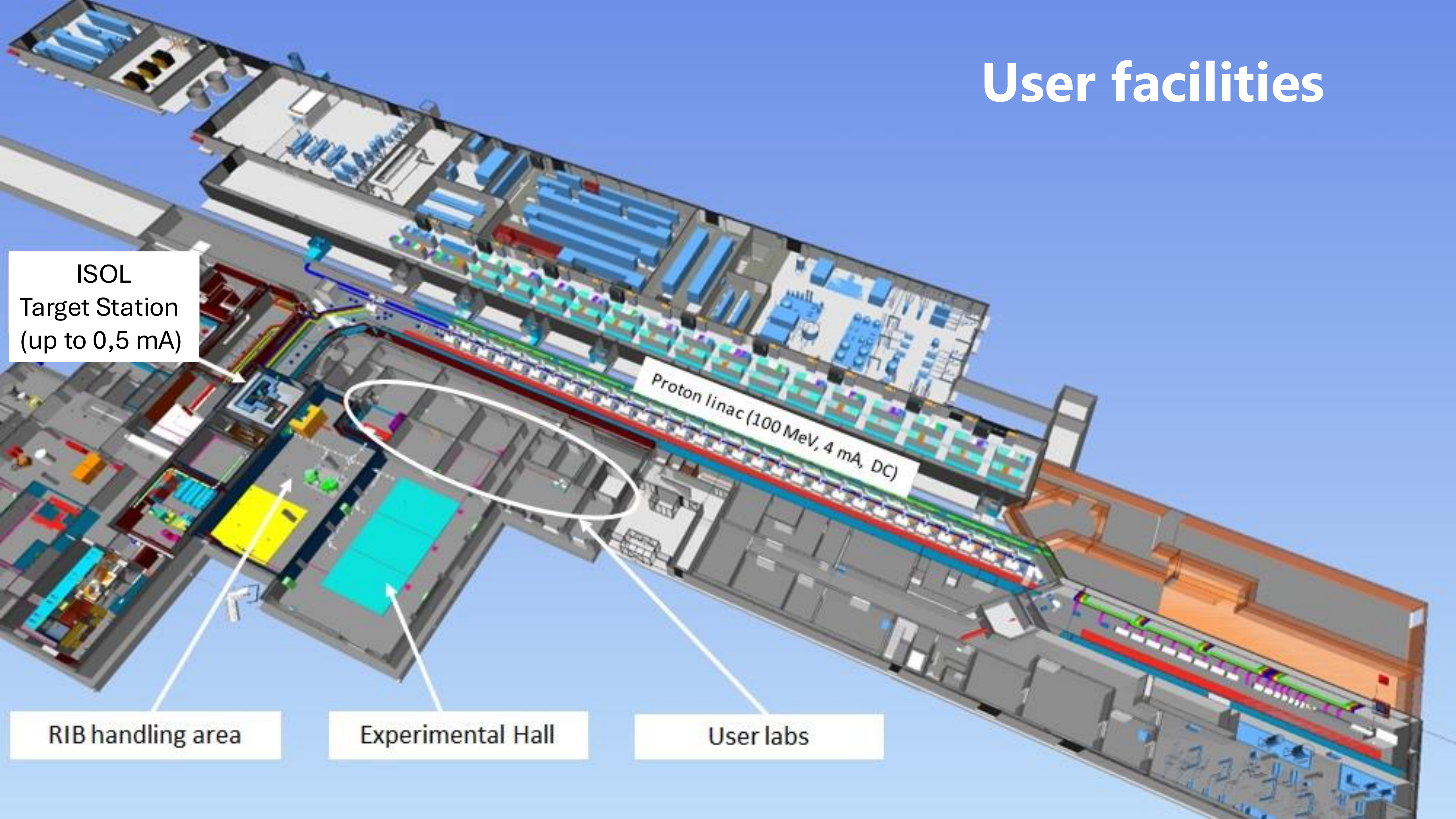
Construction

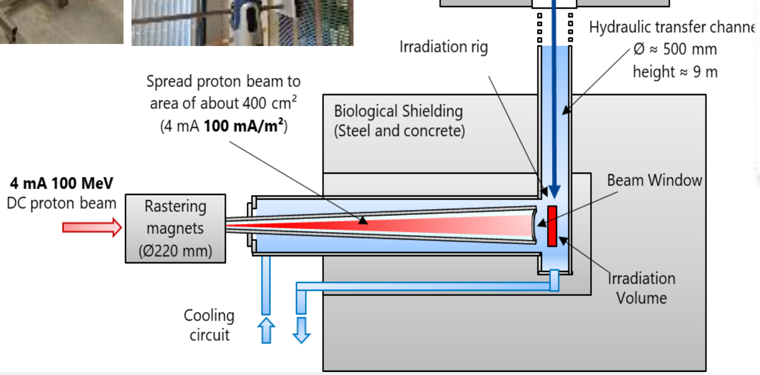
Beam Commissioning



- **Phase 2 and 3 implemented beyond 2030**
- **Reactor commissioning planned from 2037**

User facilities





Full Power facility

Beam dump for testing LINAC reliability,
Fusion-material irradiation with p & n

ISOL@MYRRHA systems

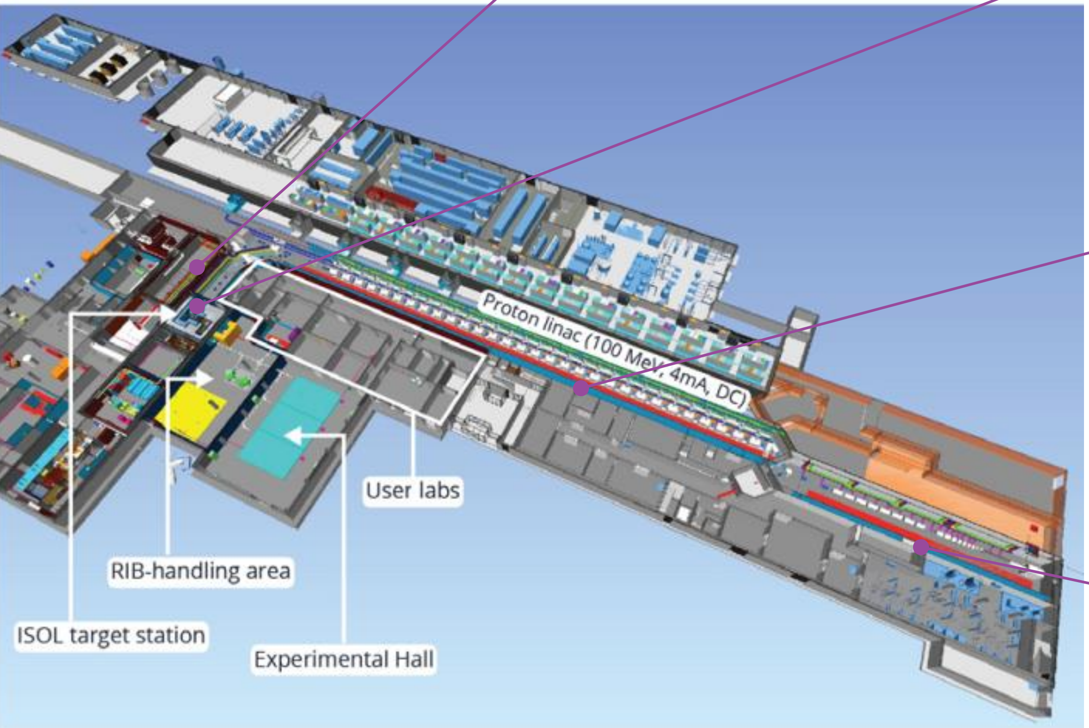
under advanced prototyping

LINAC components

Under manufacturing

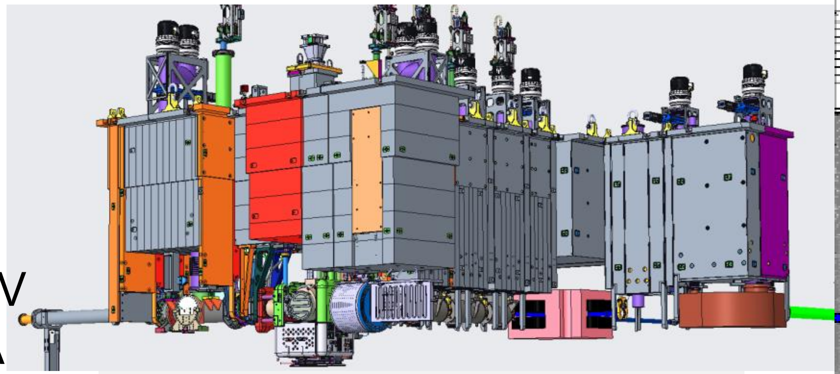
Injector

ITS Constructed & tested in LLN,
Transfer for reassembly in Mol



ISOL@MYRRHA systems

100 MeV
500 µA

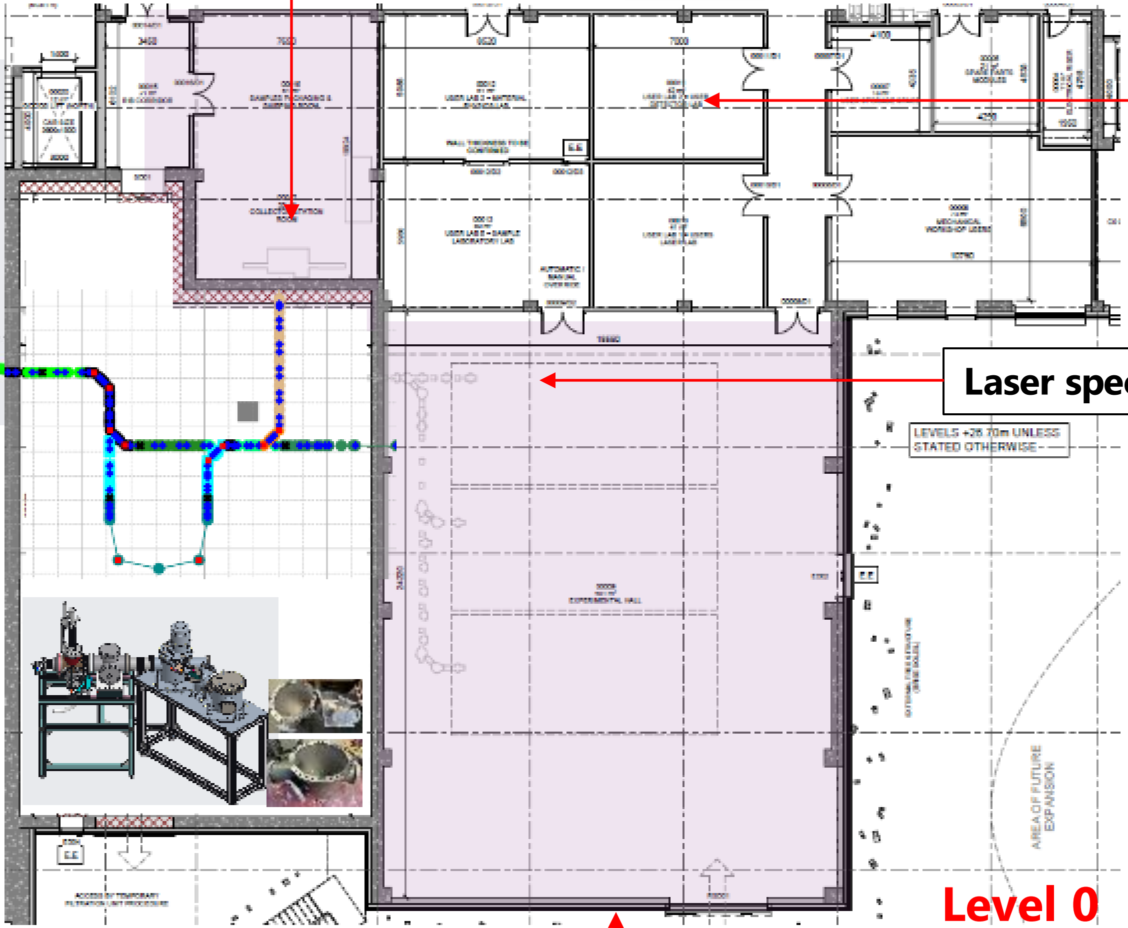


Inspired by TRIUMF-ARIEL

Modular design
2 Project Agreements

Isotope Collector Station (medical isotopes)

User Labs (Solid-state physics, laser spectroscopy, etc)



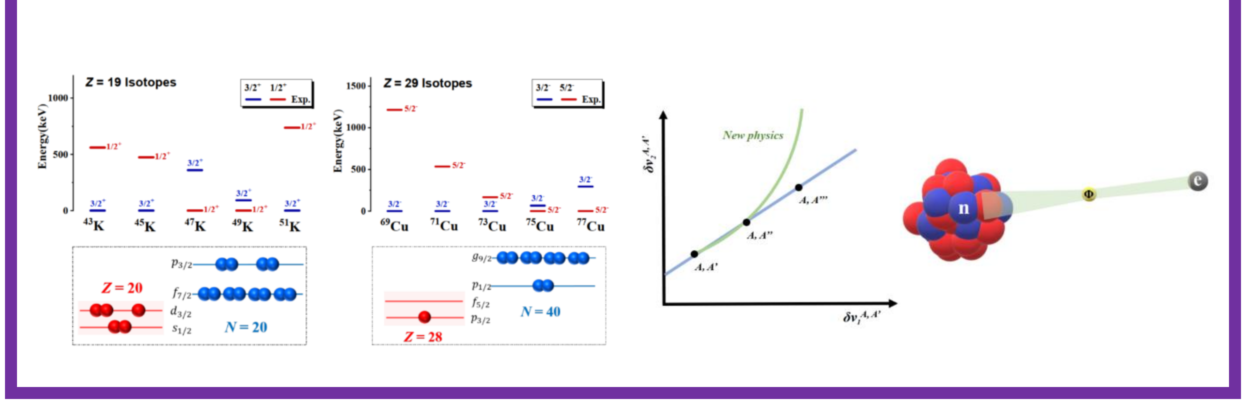
Laser spectroscopy beamline

Courtesy of Agota Koszorus (KU Leuven, SCK CEN)

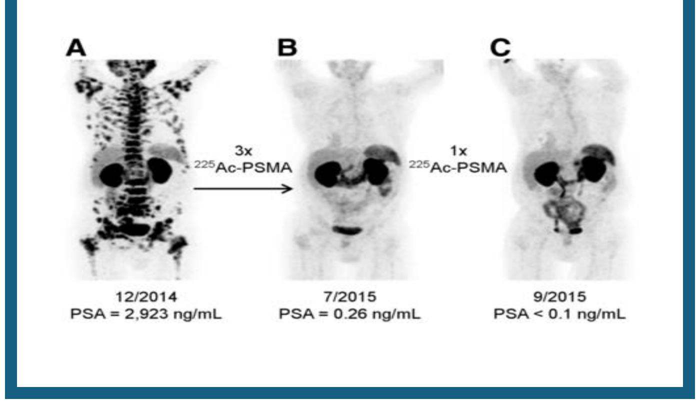
Floor-space and services available for installing experimental setups

ISOL@MYRRHA – Applications & users

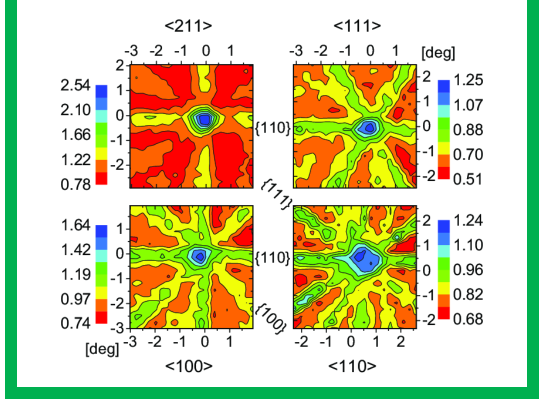
Fundamental nuclear physics



Innovative Medical Isotopes



Solid-state physics



- Emerging infrastructure recommended in **NuPECC** Long Range Plan

- Emerging infrastructure in **PRISMAP** *(access platform with leading institutes in the supply chain for European biomedical researchers)*

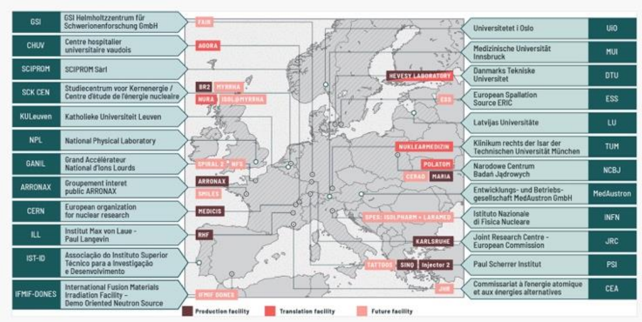
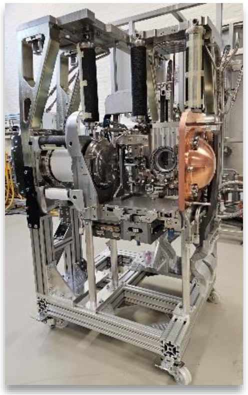


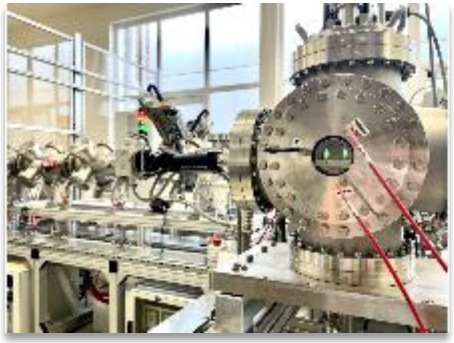
Image credits: DOI:10.1016/j.ppnp.2022.104005, DOI:10.1007/s00259-023-06165-9, DOI:10.1103/PhysRevC.100.024315, https://www.nupecc.org/lrp2024/Documents/nupecc_lrp2024__video_kurz.mp4, https://www.prismap.eu/

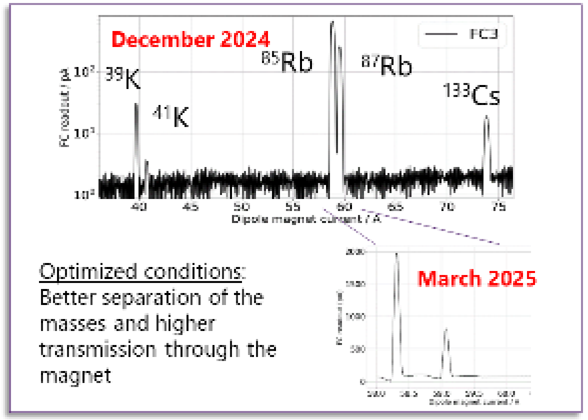
Status ISOL systems

- **Advancing the technical design**
  - Basic design of ISOL@MYRRHA systems either completed/advancing
- **Prototyping**
  - ISOL system offline – constructed, operational
  - Isotope-Collector station – under tests
  - TISA & RDS - under manufacturing
  - Target Module - constructed
    -> ARIEL front-end (collab. TRIUMF)



- **1st separated ion beam**

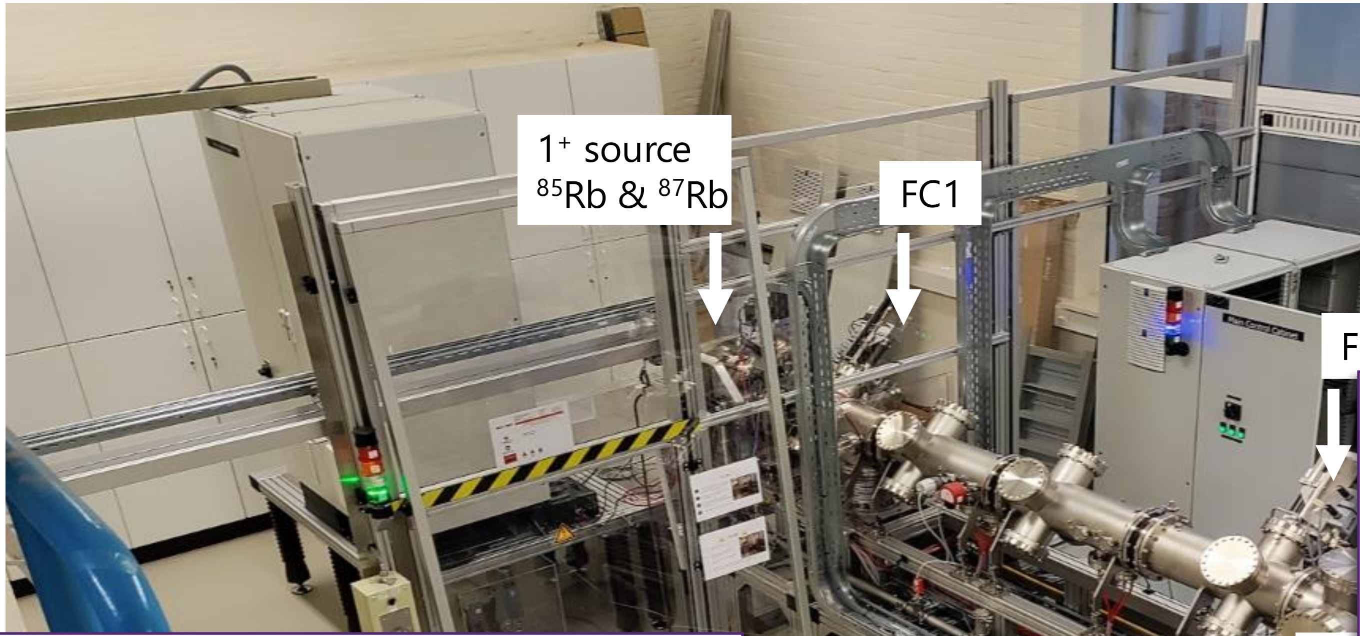


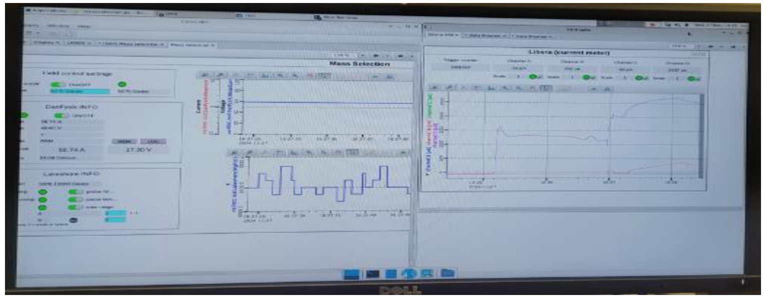


- **R&D program**
  @ SCK CEN & external labs

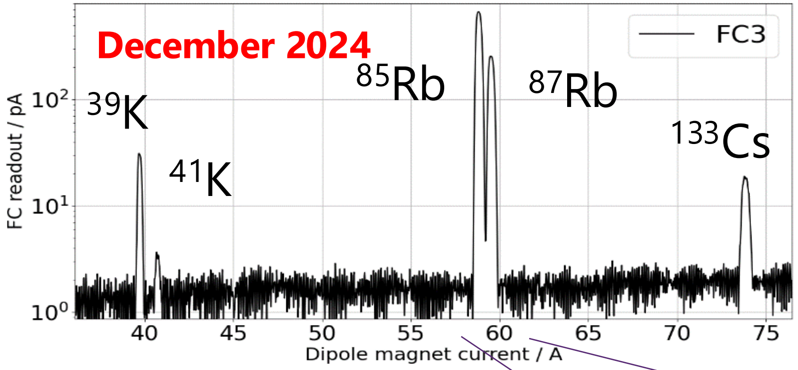
R&D infrastructure at SCK CEN
- ISOL@MYRRHA labs
  - ISOFF
  - Material & Thermal test systems
  - IMRILS lab
- Materials-research laboratories

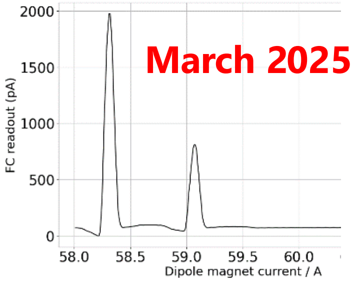
ISOL@MYRRHA off-line system commissioned in Labo 2





(27/11/24)
Beam transported to the end of the beam line





<u>Optimized conditions</u>:
Better separation of the masses and higher transmission through the magnet

Slide courtesy of L. Popescu

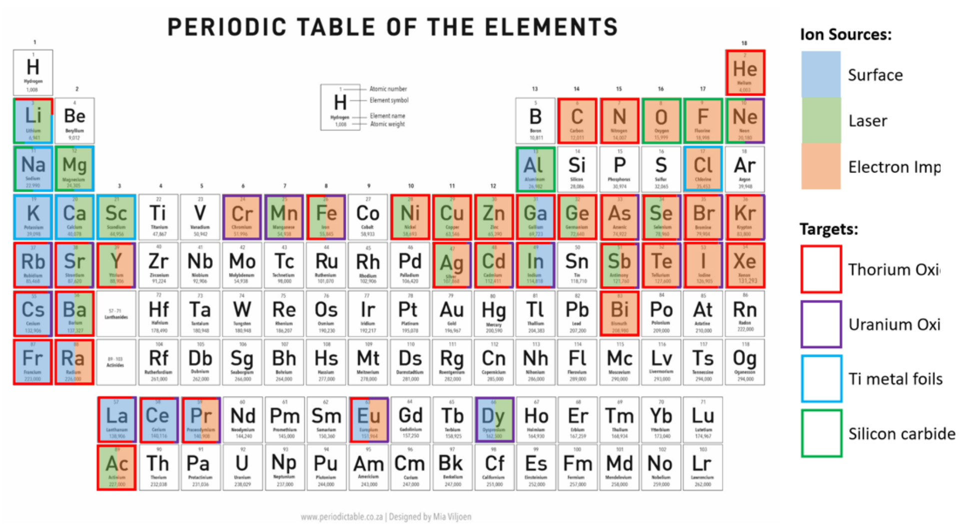
Day-1 yields at ISOL@MYRRHA

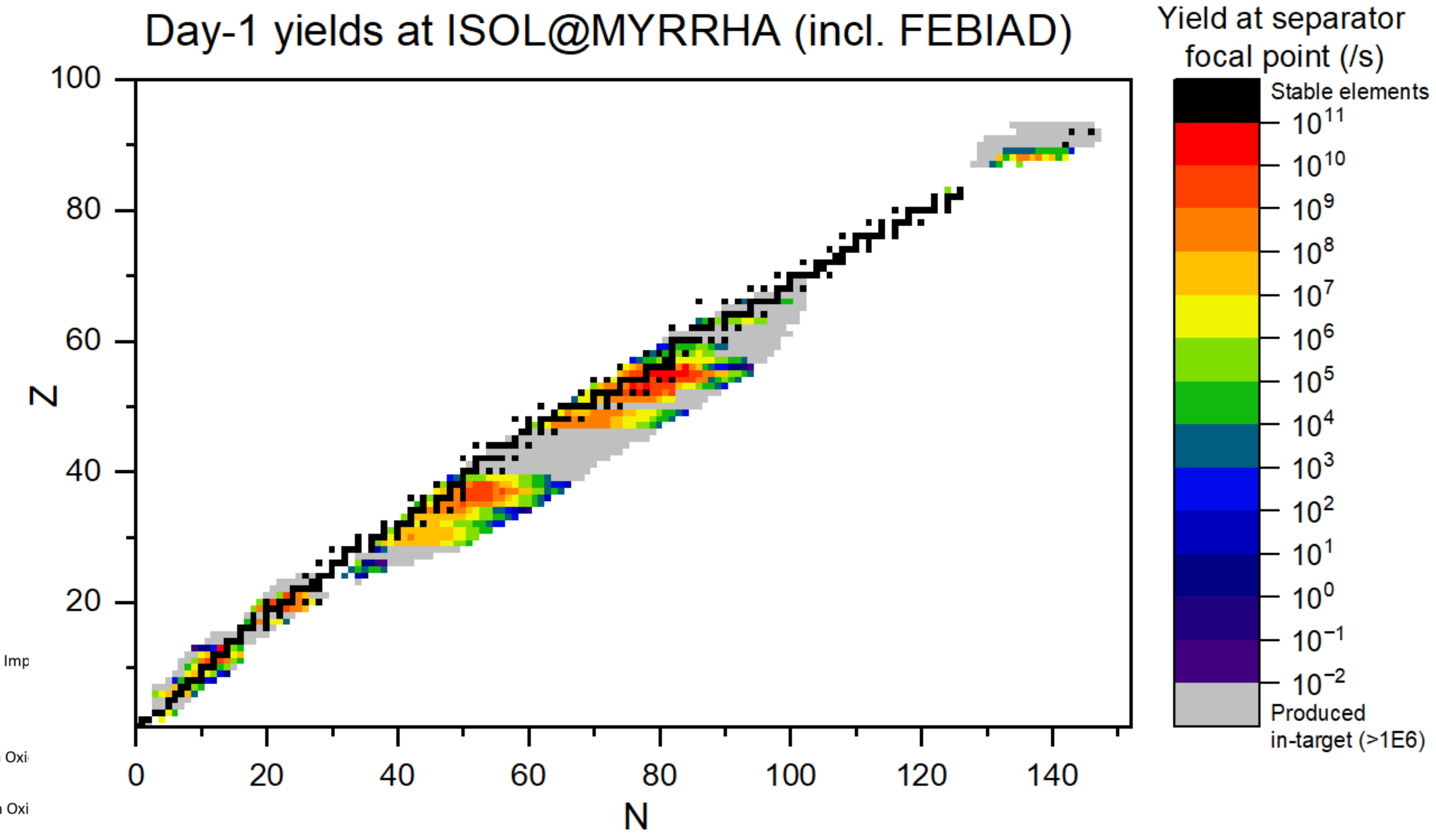
Targets chosen for day-1:

- SiC
- Ti
- ThO_2
- UO_2

Ion Sources for day-1:

- Surface Ion Source
- Laser ionization
- (FEBIAD)

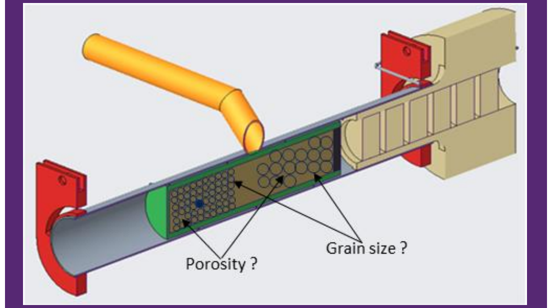




Available: Report with all day-1 user yields from the above plot!
(In the CERN Box folder used for the project agreements)

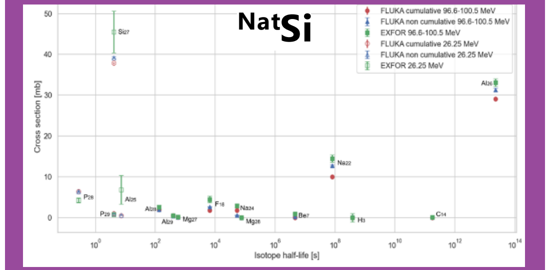
Day-1 targets

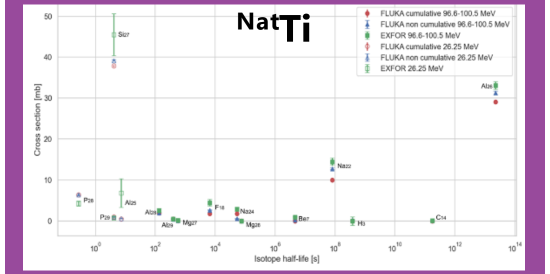
Produce $^{22\sim28}$Al & $^{23\sim29}$Mg from Si- or Ti-based targets



Leading material candidate SiC

Cross section verification

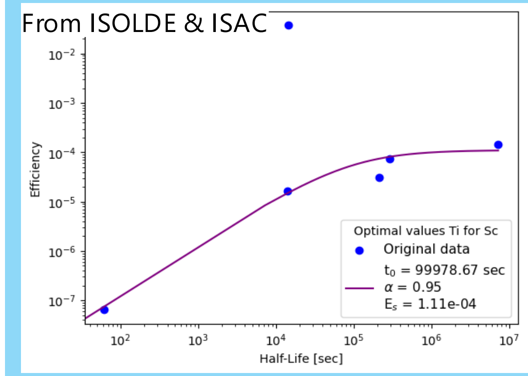




General good agreement

Preliminary Yield

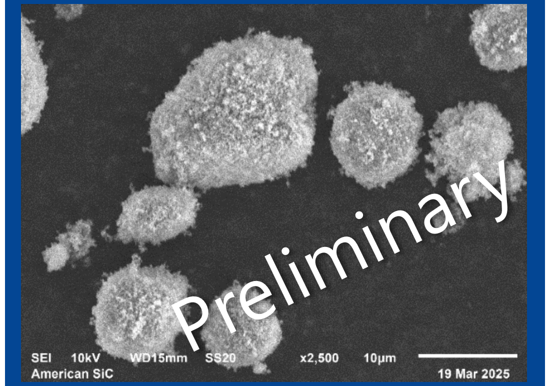
In target production rate [#/uC]				
^{24}Al	^{25}Al	^{26g}Al	^{22}Mg	^{23}Mg
$8\ 10^{7}$	$4\ 10^{9}$	$5\ 10^{10}$	$2\ 10^{8}$	$4\ 10^{9}$



Esimated Yield [#/uC]				
^{24}Al	^{25}Al	^{26g}Al	^{22}Mg	^{23}Mg
$6\ 10^{2}$	$3\ 10^{4}$	$7\ 10^{9}$	$2\ 10^{6}$	$1\ 10^{8}$

Method established

Microstructure analysis*



Revealed powder grain agglomerates

*SiC powded from CERN
(collab. on SiC target material)

International R&D network (1)

Universities

Research

International R&D network (2)

Private Sector

TRACTEBEL ENGIE
EMPRESARIOS AGRUPADOS
iba
ACS ACCELERATORS AND CRYOGENIC SYSTEMS
THALES
ADEX
SENER
research instruments
BEVATECH
NNC
OXFORD TECHNOLOGIES *
COSYLAB
NTG
TA TechnicAtome
ANSALDO NUCLEARE Ansaldo Energia Group

Beyond EU

JAEA

Source: SCK CEN MYRRHA Project Team
* Acquired by Veolia

- MYRRHA is a unique large research infrastructure. Closing the fuel cycle including P&T is a must for achieving sustainable nuclear energy as part of a CO_2 neutral energy transition.

- MYRRHA is under construction and reactor pre-licensing is completed.

- This is the only multipurpose fast spectrum research reactor in the EU aiming at realization.

- Belgium is calling on international participation and contribution.

SCK CEN
Belgian Nuclear Research Centre

Foundation of Public Utility

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