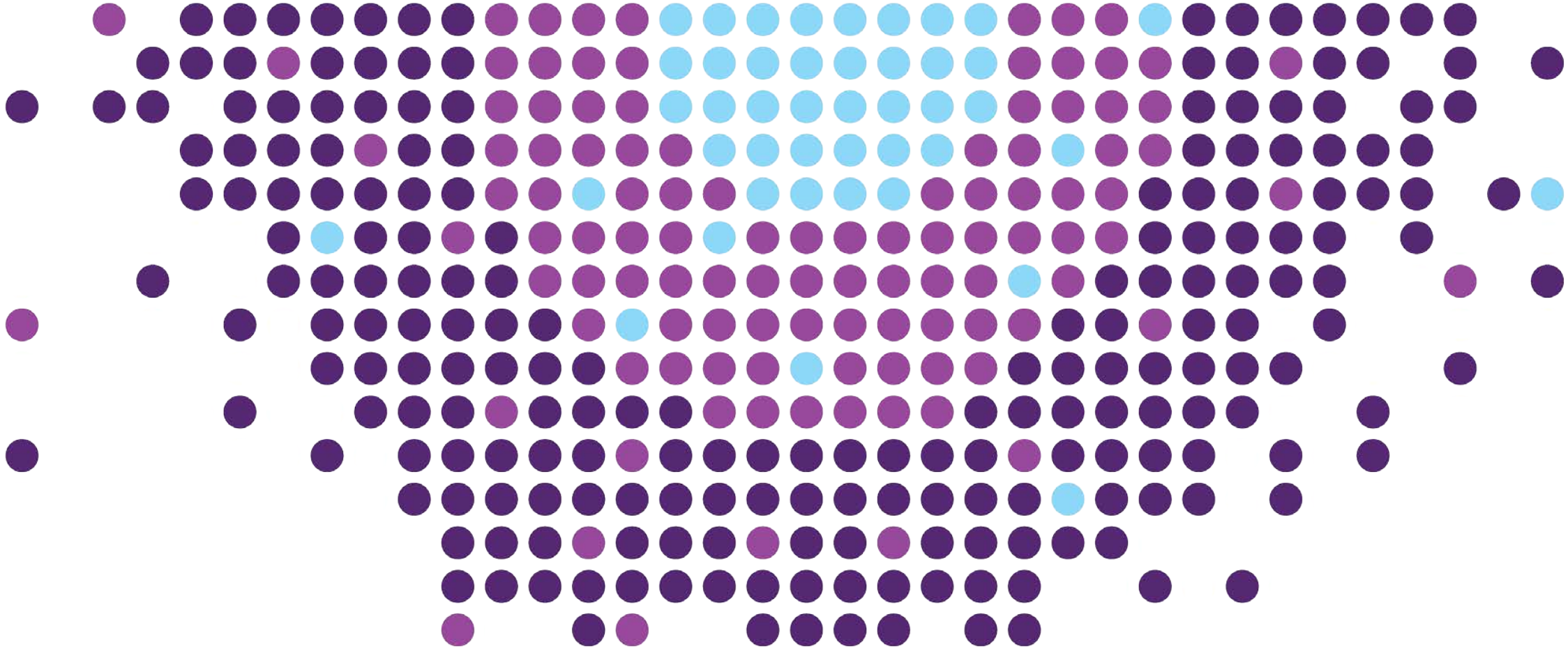


sck cen
Belgian Nuclear Research Centre

Dr. Daniel Berkowitz (SCK CEN)

MINERVA Cryomodules and associated Cryogenic System (MYRRHA Phase 1)

29-MAR-2023
European Cryogenic Days

Scope

1. MYRRHA Phase 1 (=MINERVA)
2. MINERVA's SRF LINAC and Cryogenic System
3. Spoke Cryomodules (prototype and series)
4. Summary

MYRRHA

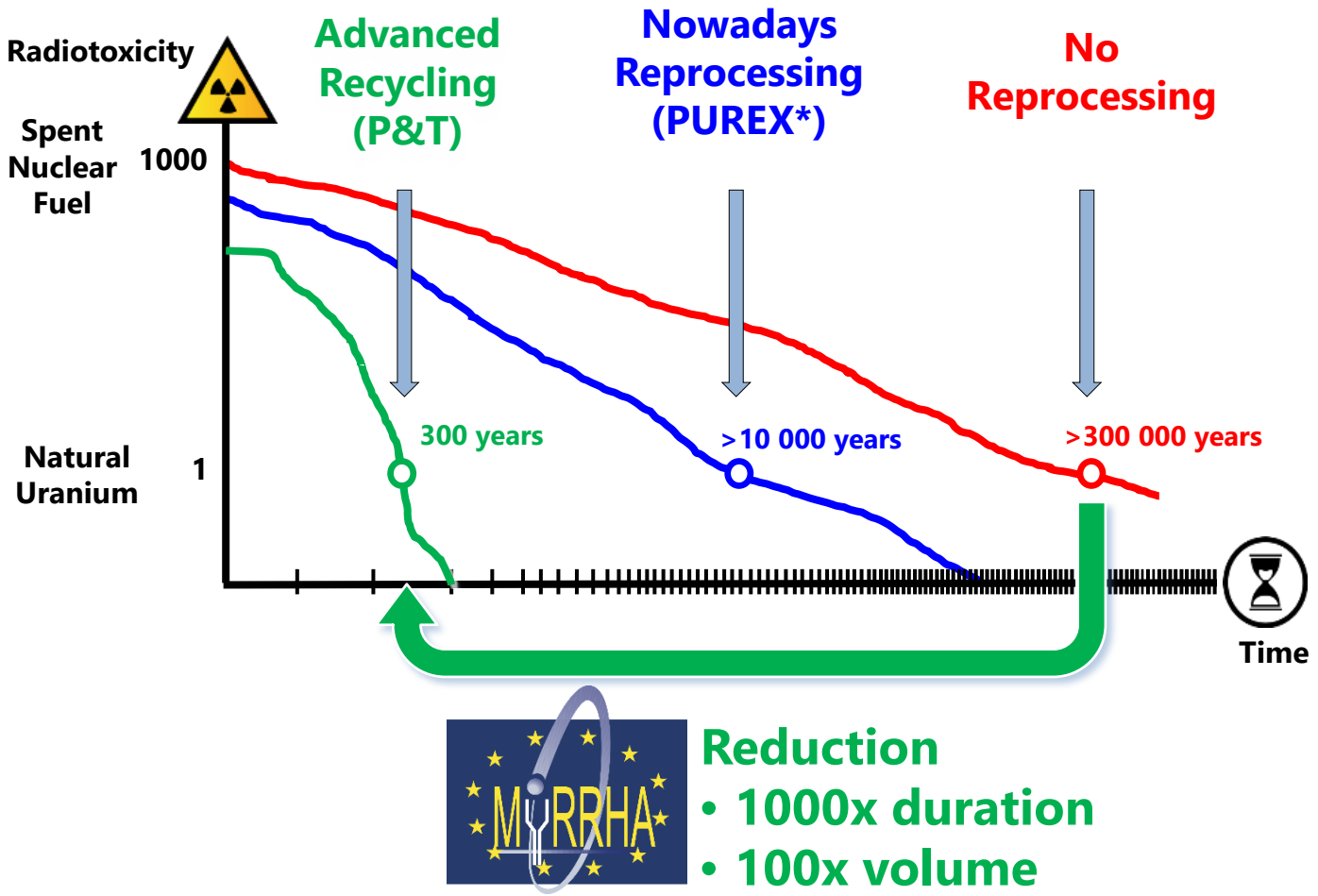
... and MINERVA (= MYRRHA Phase 1)

Why MYRRHA?

- **Nuclear waste treatment**
  - Allow for **Partitioning & Transmutation** of nuclear waste in order to reduce its radio-toxicity.
  - Reduction of 100x in volume and 1000x in duration.

- Other applications
  - Flexible irradiation in replacement of the SCK CEN MTR BR2 (100 MW).
  - Fast spectrum testing. An attractive facility in Europe, beyond 2010 complementary to RJH (FR).
  - Production of medical radio-isotopes
  - Education and training

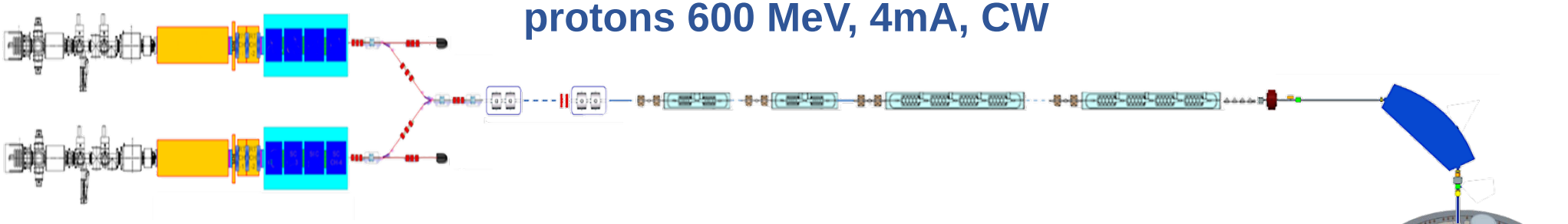
Reduction of radio-toxicity of nuclear waste



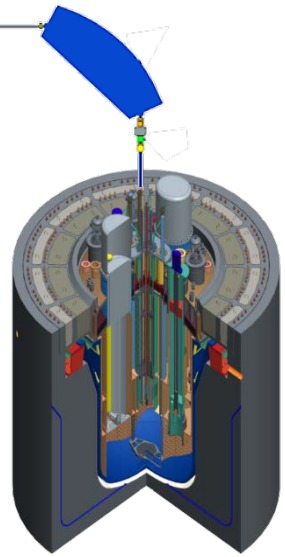
The MYRRHA Project

- **MYRRHA,** a **M**ultipurpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications
- MYRRHA is an **A**ccelerator **D**riven **S**ystem (ADS)
  - A full ADS demo facility at pre-industrial scale, where a "subcritical" reactor core is coupled to a proton accelerator.
  - The particle beam is needed to sustain the nuclear reaction.

Linear Accelerator
protons 600 MeV, 4mA, CW



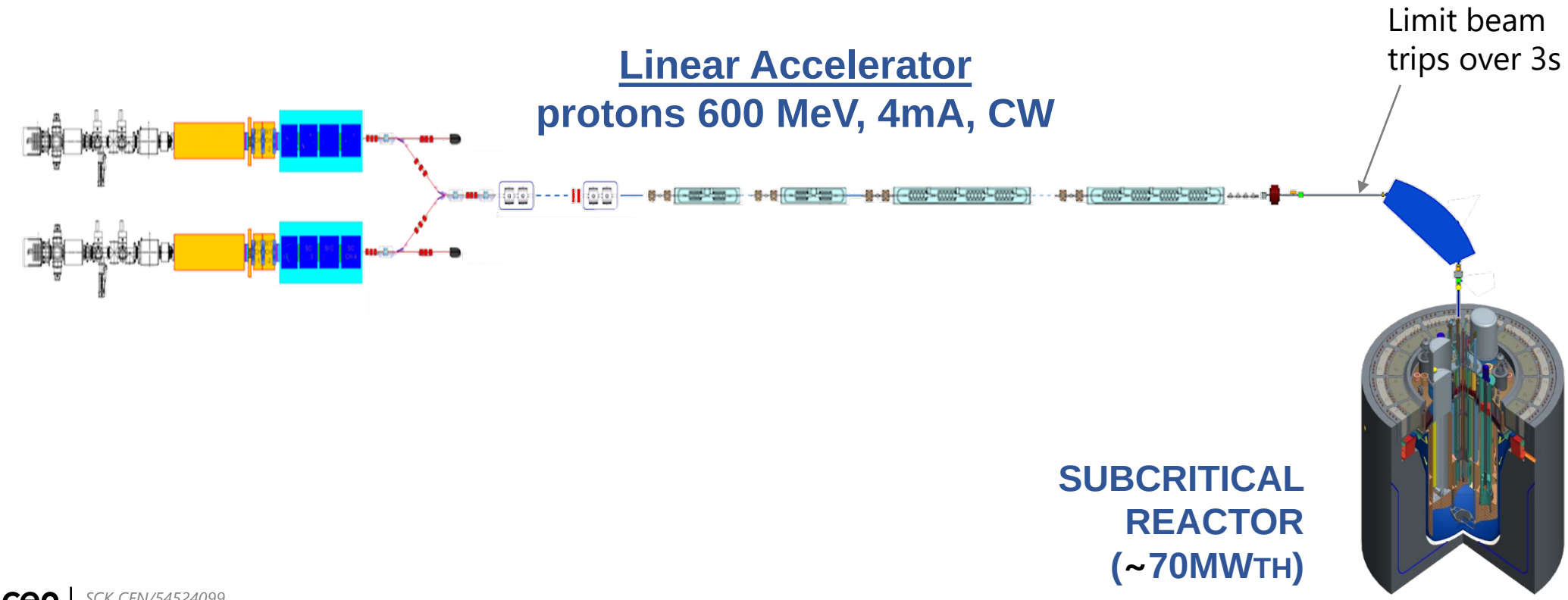
SUBCRITICAL REACTOR (~70MWTH)



If the linac stops, the reactor stops.

Reliability is a core requirement

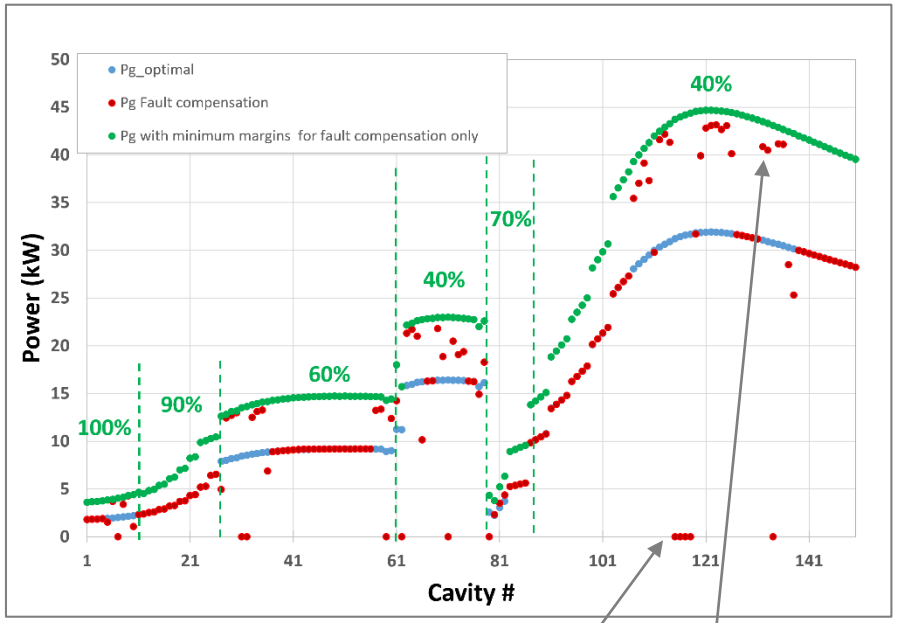
- **Beam trips**…
  - … cause severe thermal stress on the reactor materials/components limiting its lifetime.
  - … lead to a time-consuming restart of the reactor limiting its availability.
- Reliability requirement
  - Beam trips shall be resolved within 3 seconds to be transparent to the reactor
  - Max 10 beam trips > 3s within 90 day operational run (MTBF > 250 h)



Fault tolerance, key to achieve high reliability

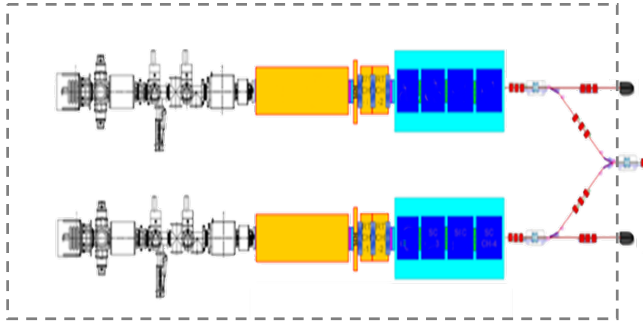
- Fault tolerance in MYRRHA
  - Parallel redundancy of injector section
  - Serial redundancy in superconducting RF (SRF) linac (online systems take over workload of failed systems)
- Only 3 seconds for failure detection, reconfiguration, and full beam power ramp
- For trips on RF systems, local and global compensation schemes are under study

Fault compensation of RF systems



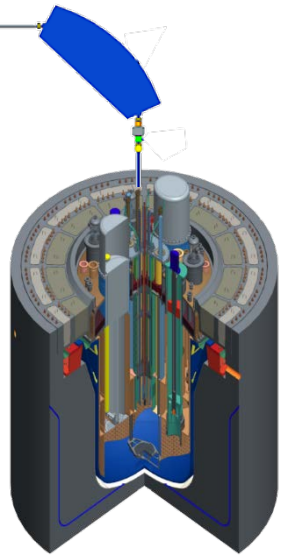
Ref. "F. Bouly. LINAC2020 (in2p3-03062748)"

Linear Accelerator
protons 600 MeV, 4mA, CW



2 injectors in parallel for parallel redundancy

RF systems with sufficient operational margin for serial redundancy



SUBCRITICAL REACTOR (~70MWTH)

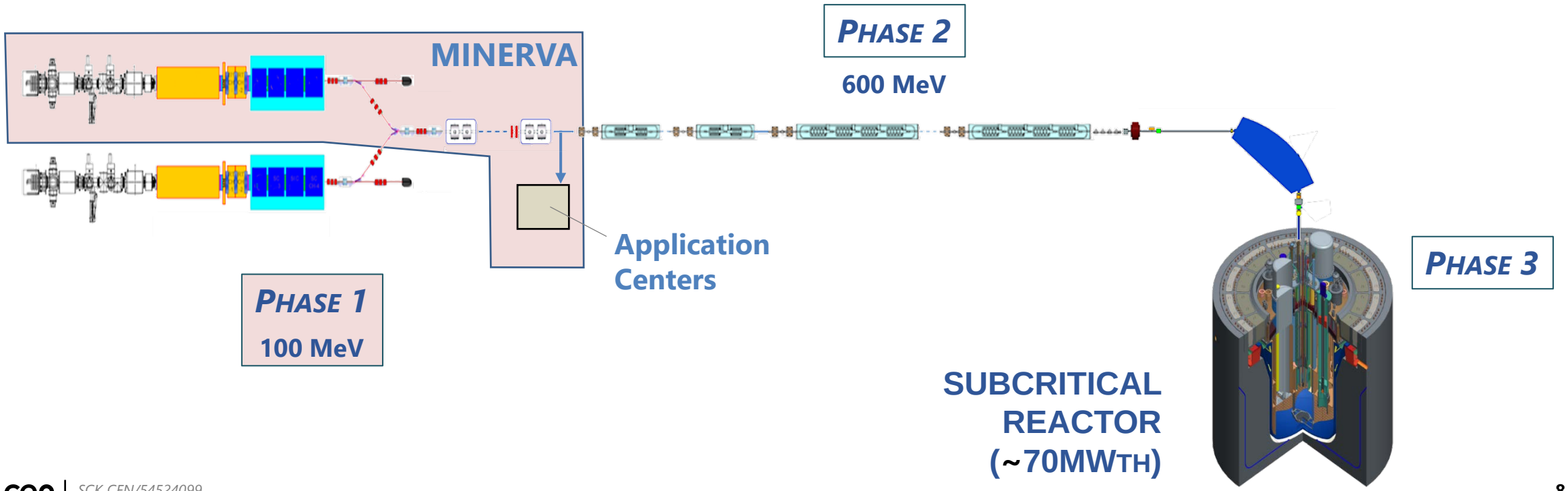
The 3 Stages of MYRRHA (1/2)

Phase 1 = **MINERVA** (fully funded since 2018)

- **100 MeV**, 4mA CW, SRF proton linac available at SCK CEN by **2027**
- Key objective: To **demonstrate reliability** as required for an Accelerator Driven System (ADS)
- Application Centers: ISOL system (100 MeV, 0.2 to 0.5 mA of beam), Full Power Facility (fusion material research, 400 kW)

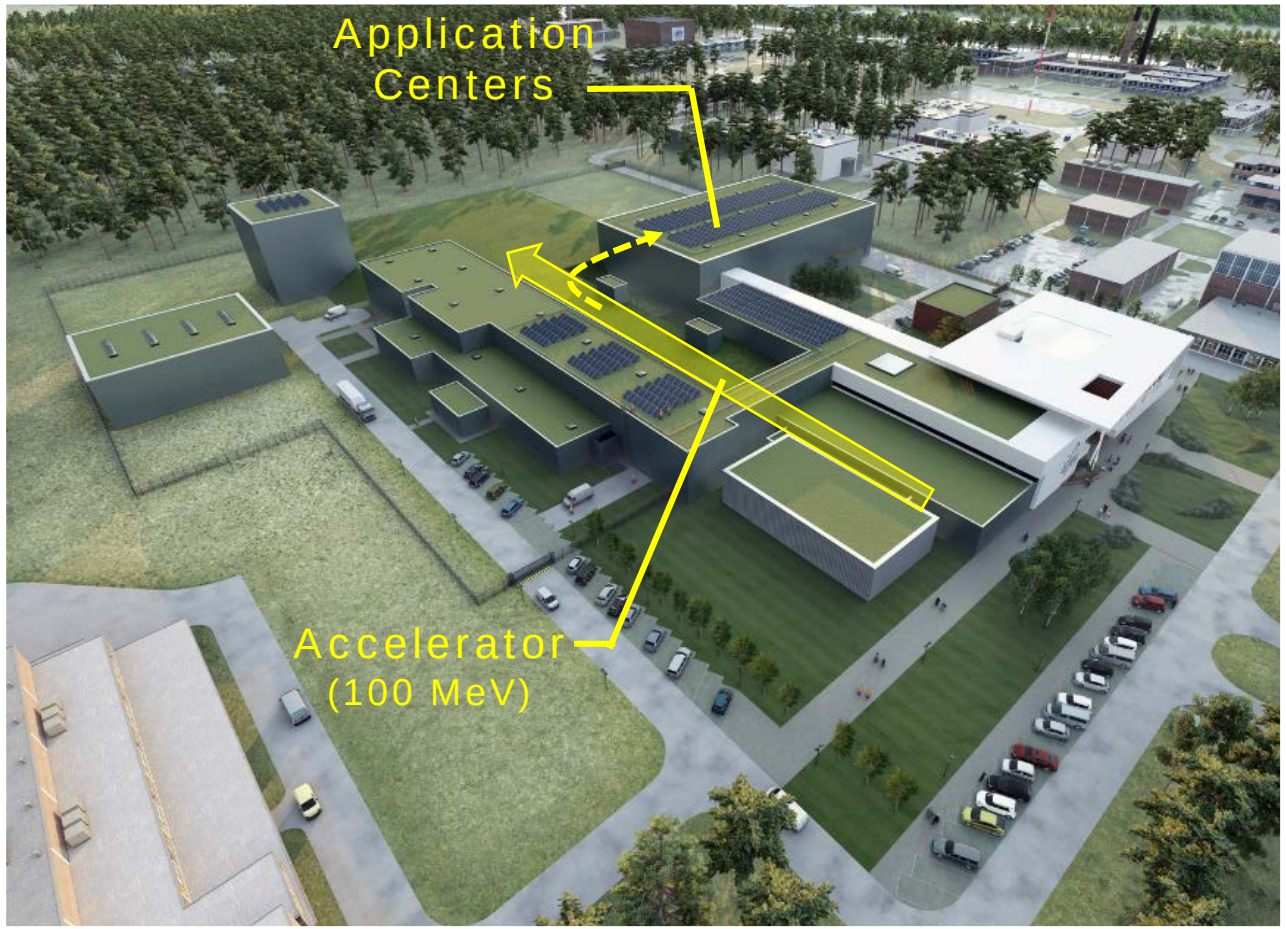
Phase 2 (expansion to 600 MeV) & Phase 3 (reactor)

- Funds available for R&D
- Subject to international funding for implementation

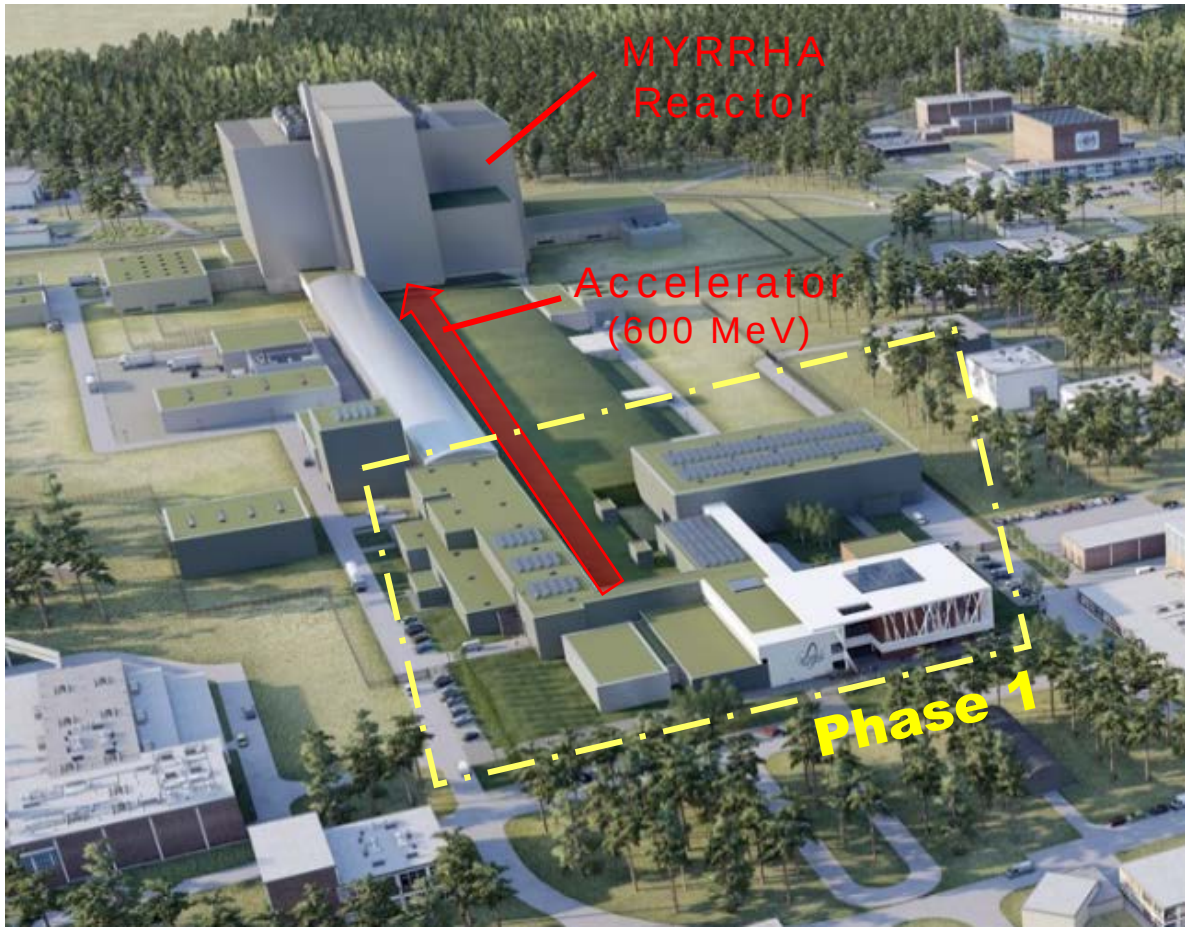


The 3 Stages of MYRRHA (2/2)

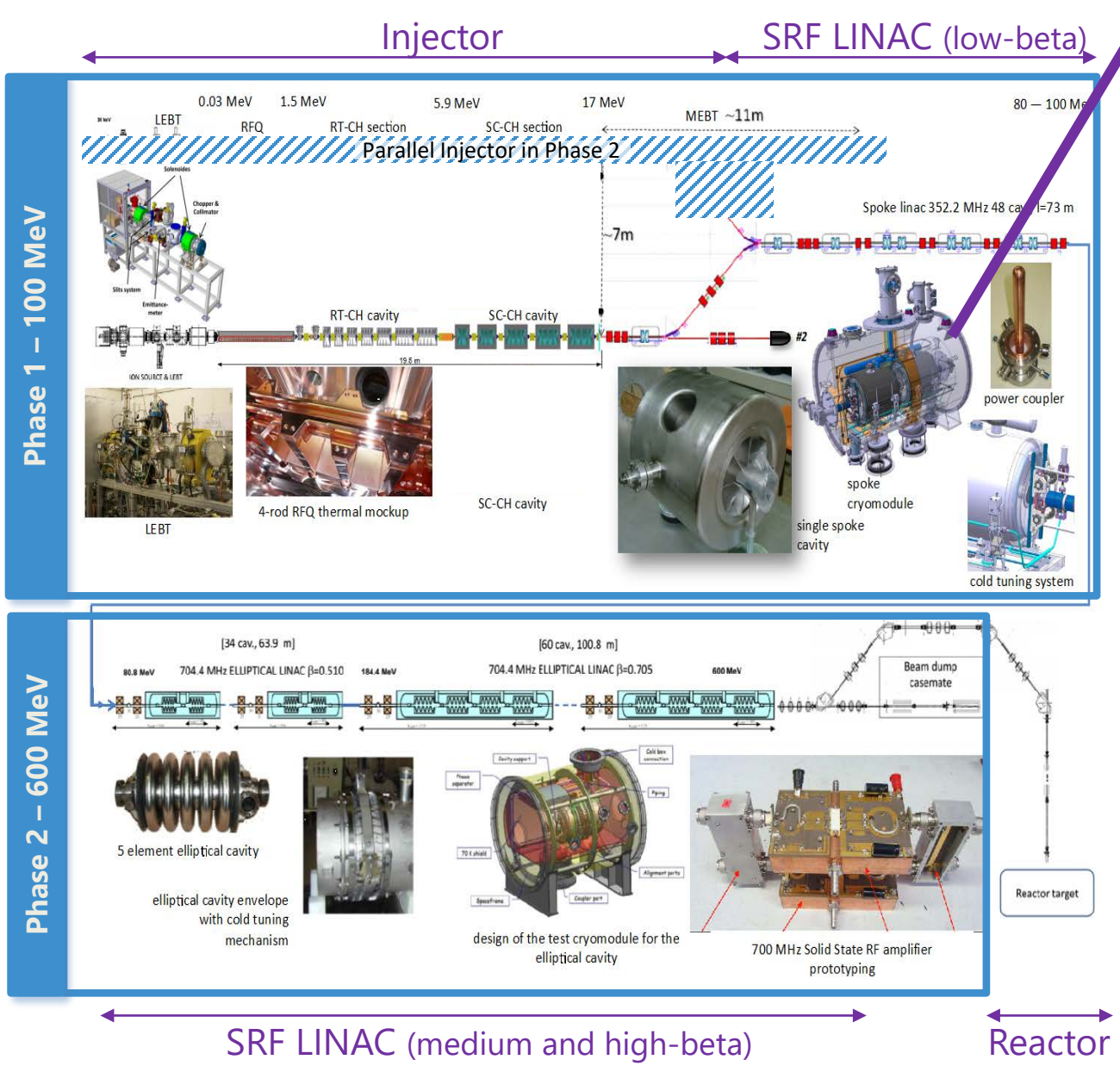
MYRRHA Phase 1 (= MINERVA)



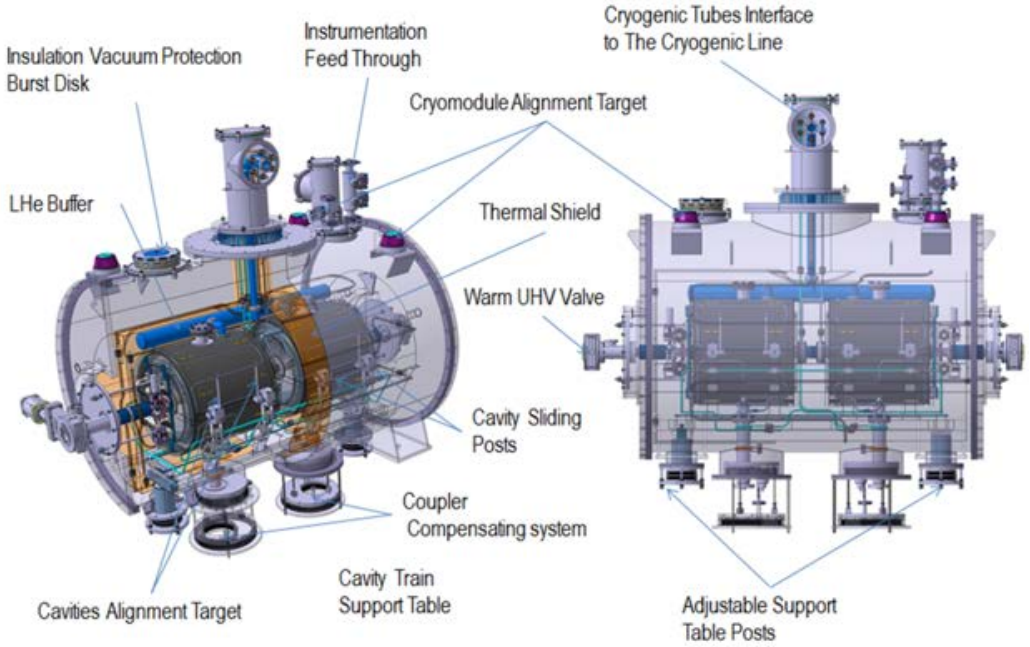
MYRRHA (fully implemented)



MYRRHA's Accelerator Technologies



Low-Beta Cryomodules



MINERVA comprises of 30x cryomodules.

- All **identical in design**
  - 2 Kelvin operation (~20W @ 2K *)
  - $\dot{Q}_{Total}$ = ~70W @ 4.5K *
  - Vacuum Vessel: L1.9m x Ø1.2m

- Each housing **2x single-spoke** SRF cavities
  - E_{acc_nom} = 7.0 MV/m (* = at E_{acc_nom})
  - E_{acc_max} = 9.1 MV/m
  - f_0 = 352.20 MHz
  - Q_0 > 5.2 x10^9*

MYRRHA's Background Studies

Courtesy F. Bouly. 2020. LINAC2020 ⟨in2p3-03062748⟩

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

End 90's : 1st accelerator projects for ADS (APT/AAA, TRASCO, ...)
2002-2005 : MYRRHA as one of the 3 reactor designs within the PDS-XADS FP5 project

Eurotrans (FP6)
MYRRHA : XT-ADS demo.
Linac 600 Mev –
R&D on reliability-
GUINEVERE & GENEPI-3C

MAX (FP7)
- Start-to-end reference design w. error study
- Prototyping : elliptical and spoke cavity, RF ampli., RFQ mock-up, CH-DTL cavities
- Reliability model
- Design Review

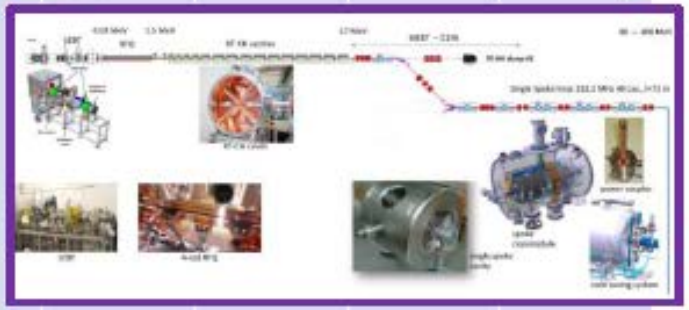
CDT (FP7) – HEBT design

MARISA (FP7)
LEBT construction – 176 MHz RF amplifier–

MYRTE (H2020)
- Injector construction & commissioning
- Beam Characterisation & Control
- SRF cavities (spoke Cryomodule – CH)
- Reliability & specific R&D

sck cen

PHASE 1 (100 MeV) : MINERVA
Construction & Commissioning of the first Accelerator section -> 100 MeV

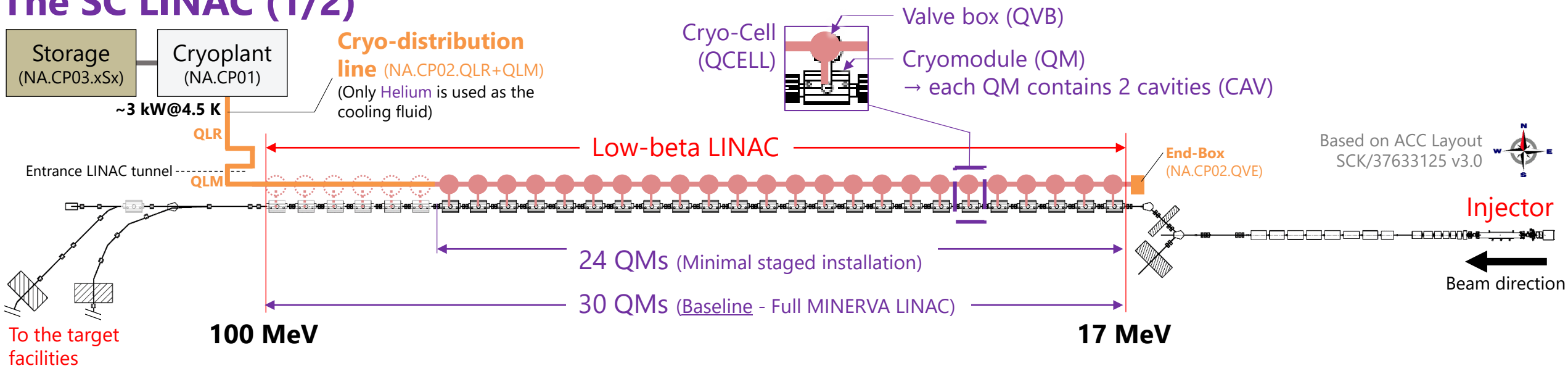


- Many background studies and designs performed during the last decades
- MINERVA is today in the implementation phase (incl. design consolidation)

MINERVA's SC LINAC

a 100 MeV, superconducting proton linac

The SC LINAC (1/2)



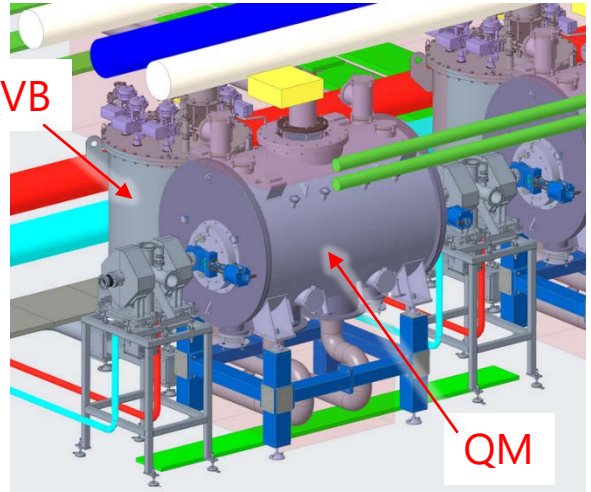
MINERVA Operational Scenarios.

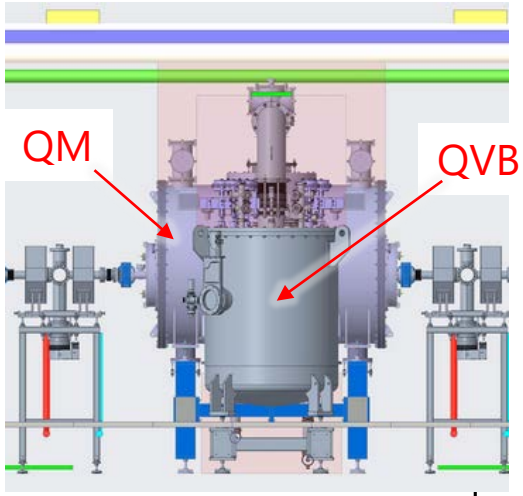
Fault-tolerance (FT) Scheme	SC LINAC configuration	
	24 QMs	**30 QMs**
Full FT	70 MeV	**100 MeV**
Standard FT	100 MeV	(125 MeV)

- Delivered proton-beam energy (MeV) depends on the actual machine configuration and fault-tolerance scheme.
- Design point for CRYO is “Full FT/30 QMs”

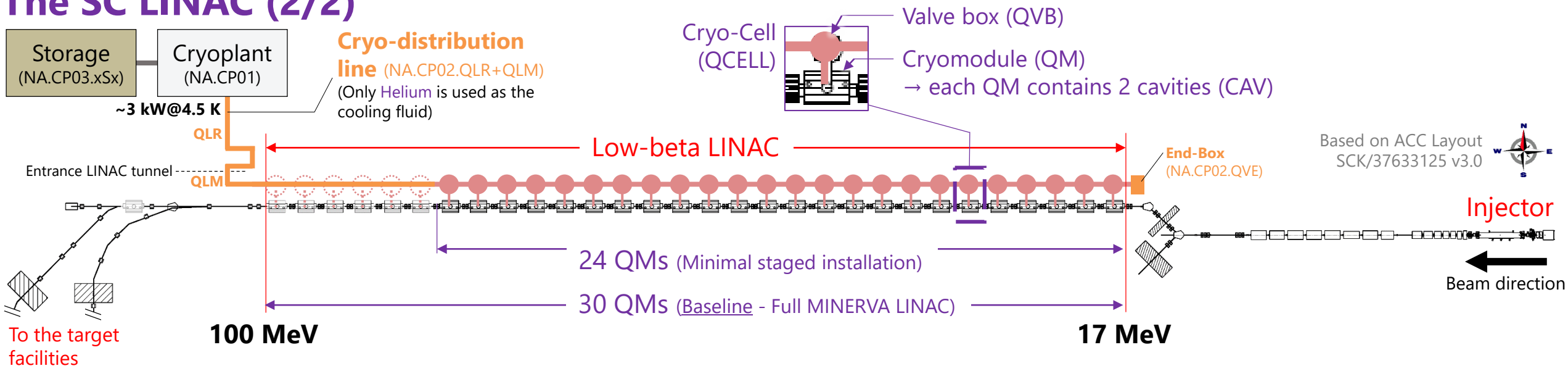
The “Cryo-Cell” (QCELL = QM + QVB)

- All MINERVA QCELLs are **identical in design**, but have different operating points (→ **different dynamic heat-loads**!).
- The QCELLs are the **only** cryogenic “users”.

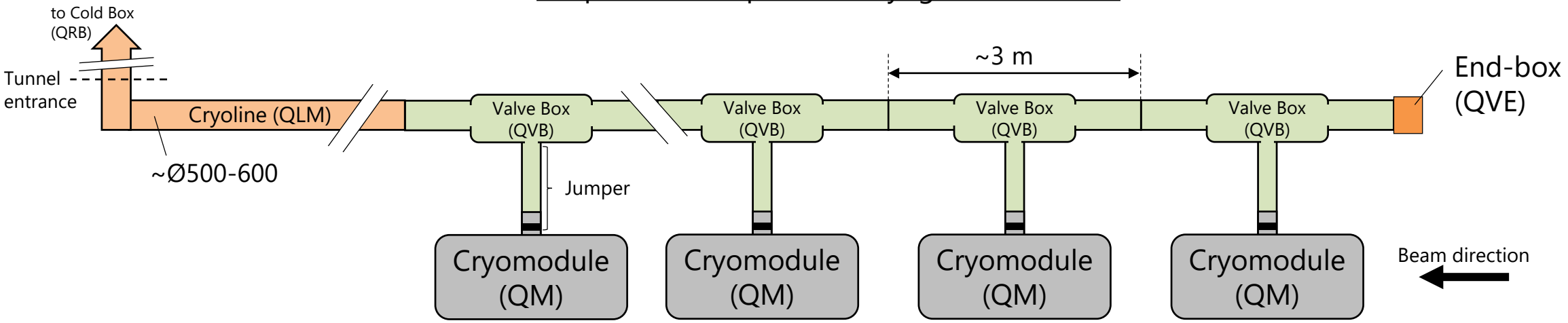




The SC LINAC (2/2)

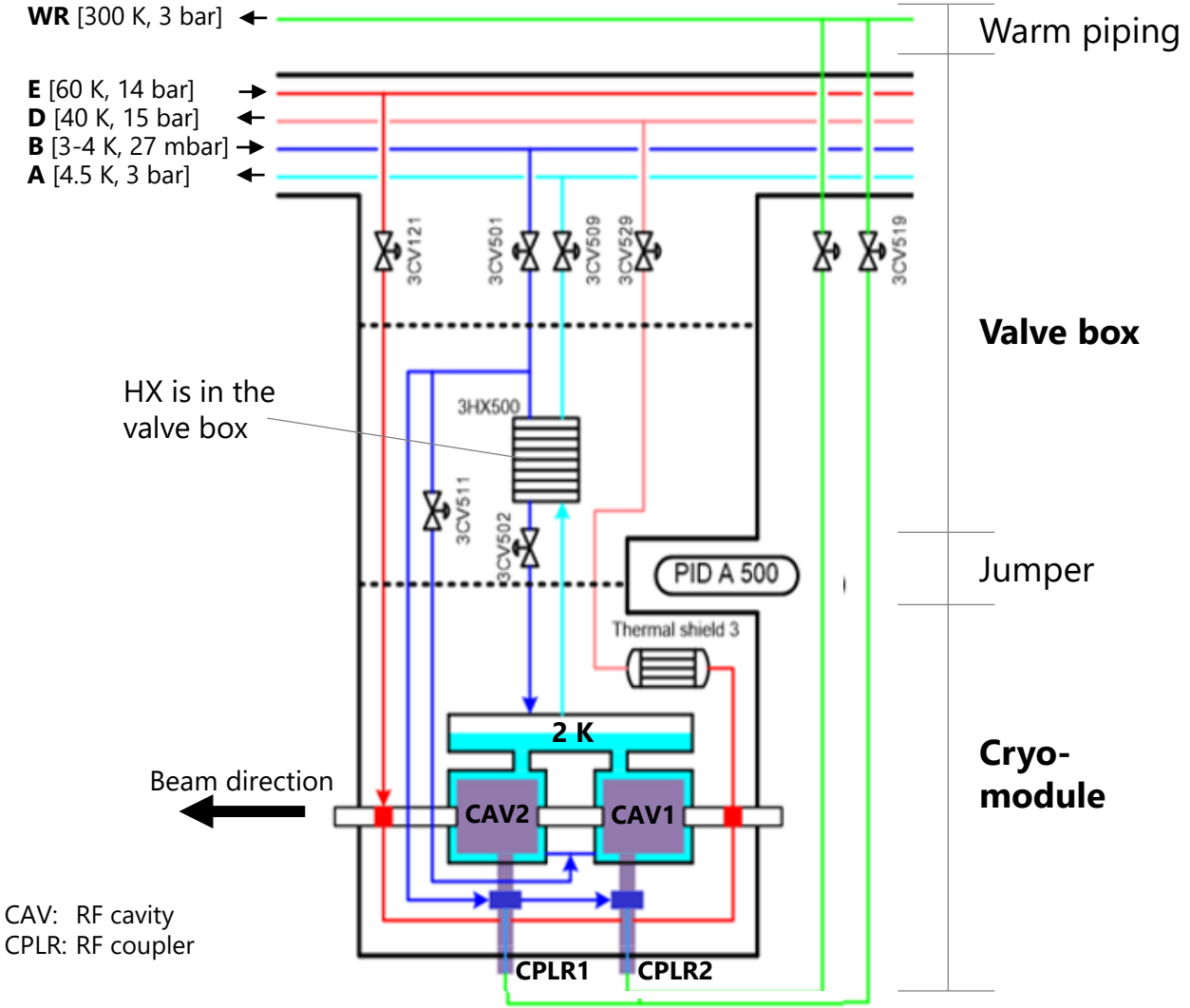


Simplified concept of the cryogenic backbone



The Cryo-Cell (QCELL)
= valve box (QVB) + cryomodule (QM)

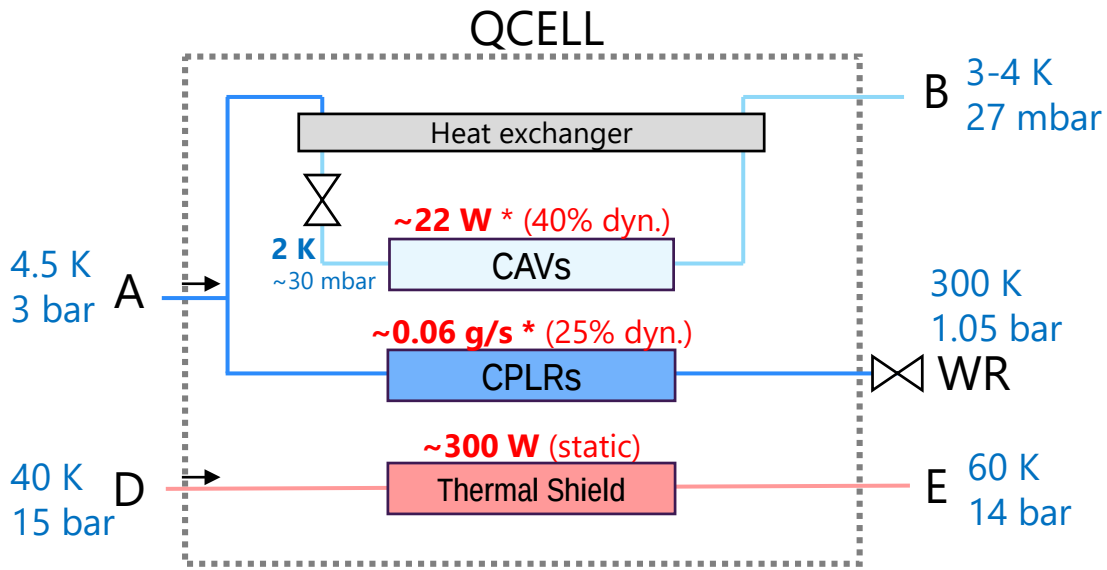
Preliminary PFD
Courtesy of CEA/DSBT, modified



CAV: RF cavity
CPLR: RF coupler

Simplified cooling circuits of a QCELL
as *seen* by the cryo-distribution

- Final interfaces and T, p values to result from cryoplant optimization.
- Heat load values [W] still preliminary and <u>without</u> margin. The dynamic contribution [%] is indicated.



* Assumes both CAVs at "nominal gradient": $E_{acc} = 7$ MV/m; $Q_0 = 5.2 \times 10^9$

Total per QCELL (<u>without</u> margin):
➢ ~80 W @4.5 K equivalent

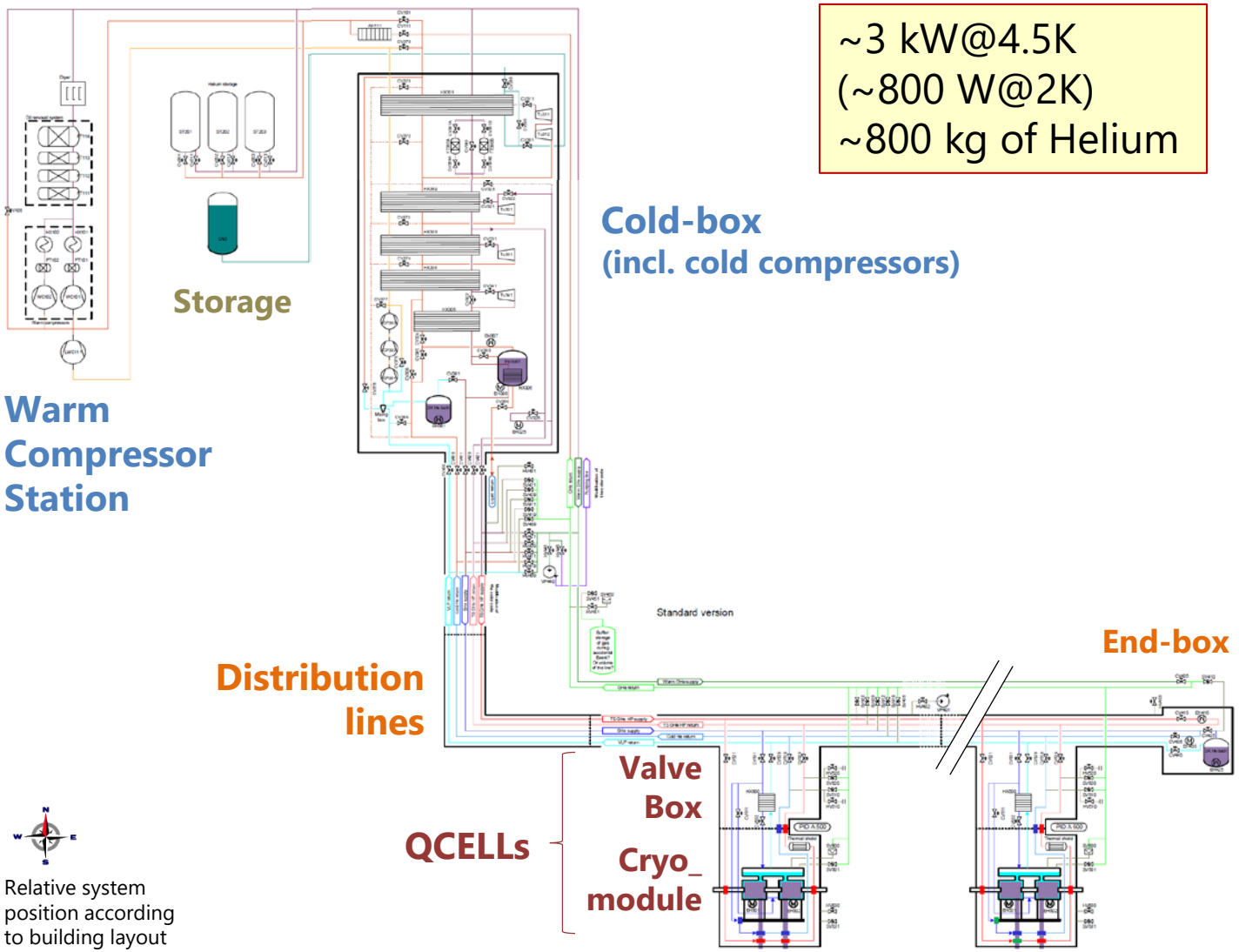
The overall Cryogenic System
(preliminary design)

- A preliminary design of the MINERVA Cryoplant developed by CEA/DSBT. The conceptual design phase is now ongoing.
  - Some changes already planned for the new iteration (i.e. modification of coupler cooling circuits)

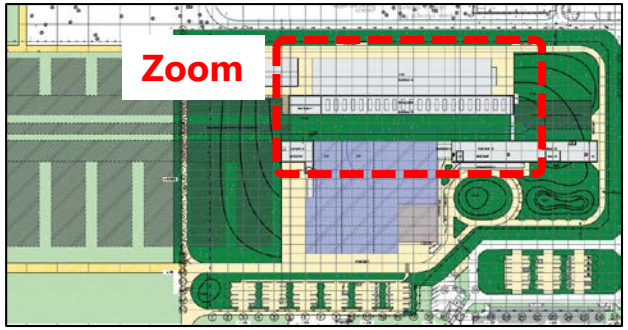
- For the cryoplant, 2 industrial pre-studies were finalized in Q1-2023 by Linde (LKT) & Air Liquide (AL-aT). The studies addressed the refrigeration process, equipment, and dimensions.

PFD of the overall Cryogenic System

Courtesy of DSBT, simplified. Coupler cooling circuits not yet modified



Building Architecture



Storage &
Warm Compressor
Station

Cold-Box

CCB Building

AUB Building

RF Gallery

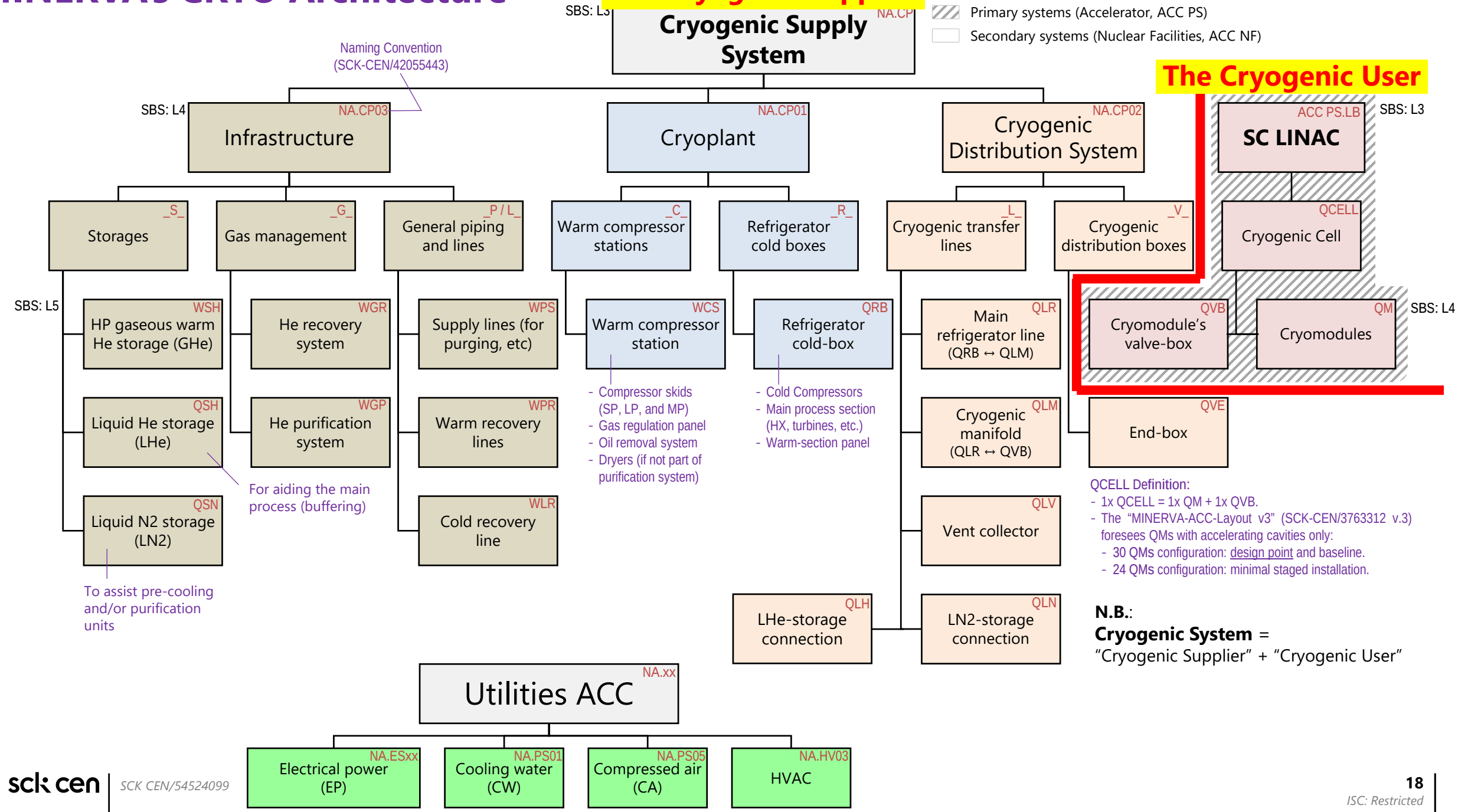
SRF LINAC

Injector

PTF / FPF

MINERVA's CRYO Architecture

(from SCK CEN-40629944)



SCK CEN-Teams for MINERVA Cryogenic System
(ATS, ICS, and NFS)

Controls

Cryogenic Supply System ("Cryogenic Supplier")

Branches:
1. Cryoplant (compressor station + cold box)
2. Cryo Distribution System (excl. QVB)
3. Infrastructure (gas storage, gas management etc.)

[+ Ancillary systems (utilities)]

NFS
Nuclear
Facilities

NFS Group
UMBS
(Utility Building Management System)

Cryogenic Supply System

CRYO for MINERVA

Cryo-Cells ("Cryogenic User")

SC LINAC with 30x Cryo-Cells
(QCELL = QM + QVB)

QM Design & Prototyping Tests

- Prototype design
- Prototype manufacturing
- Laboratory testing

QCELL Design & Implementation

- Series design consolidation
- Industrialization (tendering, etc)
- Installation & Commissioning

ATS
Accelerator
Technologies and
Systems

CIS Group
ICS
(Integrated Control System)

SCK CEN-Teams for MINERVA Cryogenic System
(ATS, ICS, and NFS)

+ Collaborations
+ Suppliers

Cryogenic Supply System ("Cryogenic Supplier")

Branches:
1. Cryoplant (compressor station + cold box)
2. Cryo Distribution System (excl. QVB)
3. Infrastructure (gas storage, gas management etc.)

[+ Ancillary systems (utilities)]

Cryogenic Supply System

cea

DSBT SBT

cryoplant industrial pre-study

Linde | Air Liquide

NFS
Nuclear Facilities

Controls

NFS Group

UMBS
(Utility Building Management System)

CRYO for MINERVA

Cryo-Cells ("Cryogenic User")

SC LINAC with 30x Cryo-Cells
(QCELL = QM + QVB)

KrioSystem – CRYOGENICS IS OUR PASSION

Zanon RESEARCH & INNOVATION SRL

sdms la chaudronnerie blanche

PMB ALCEN

MECA MAGNETIC magnetic shielding

QM Design & Prototyping Tests

cnrs IN2P3 Les deux infinis

LPSC Grenoble – Laboratoire de Physique Subatomique et de Cosmologie

cnrs IN2P3 Les deux infinis

IJCLab Irène Joliot-Curie – Laboratoire de Physique des 2 Infinis

ACS ACCELERATORS AND CRYOGENIC SYSTEMS

QCELL Design & Implementation

research instruments

FREIA – Department of Physics and Astronomy, Uppsala University

iba

OTIC Customers Support

MECA MAGNETIC magnetic shielding

ATS
Accelerator Technologies and Systems

CIS Group

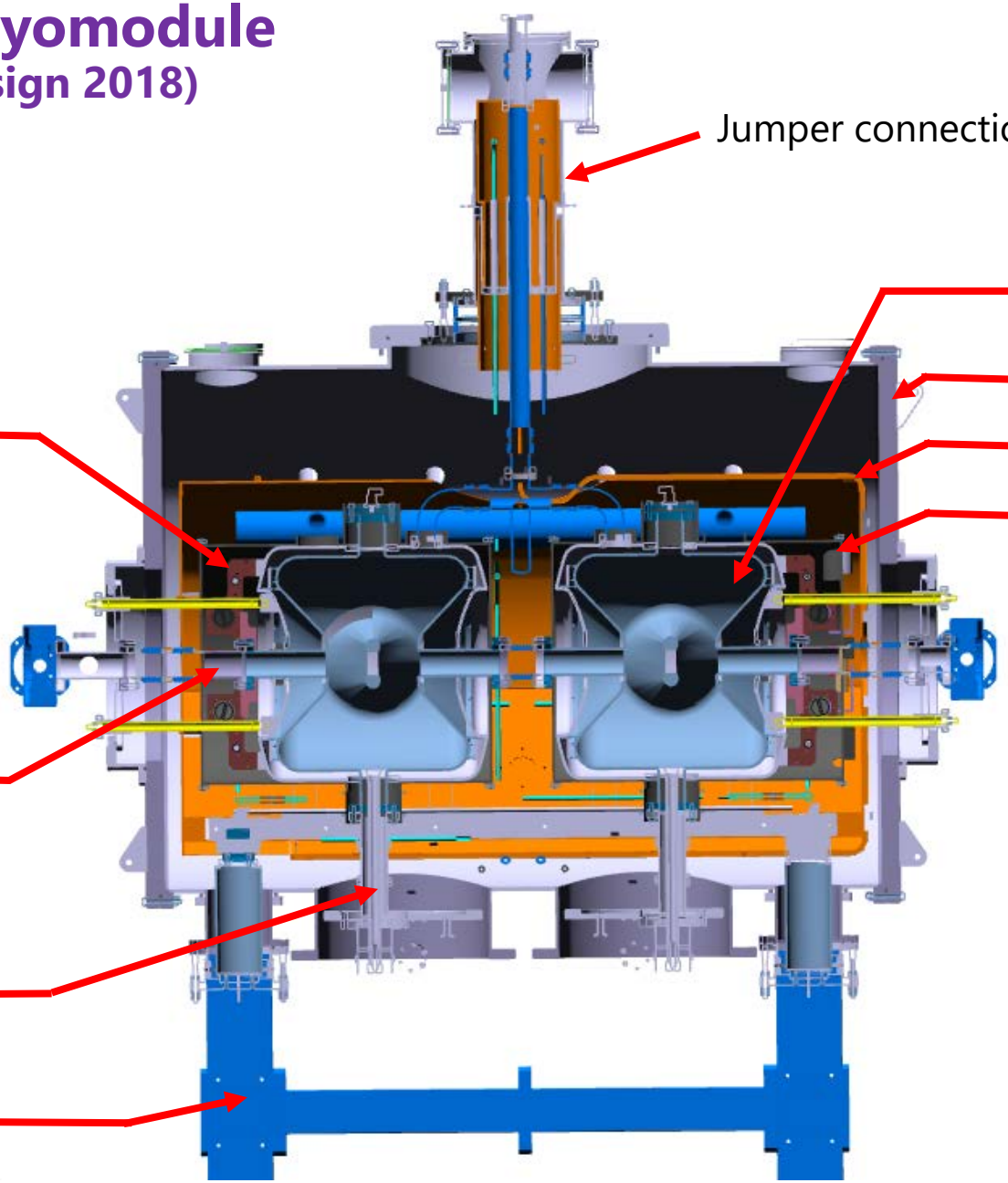
ICS
(Integrated Control System)

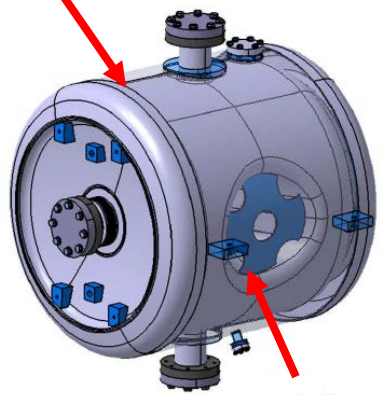
ACS ACCELERATORS AND CRYOGENIC SYSTEMS

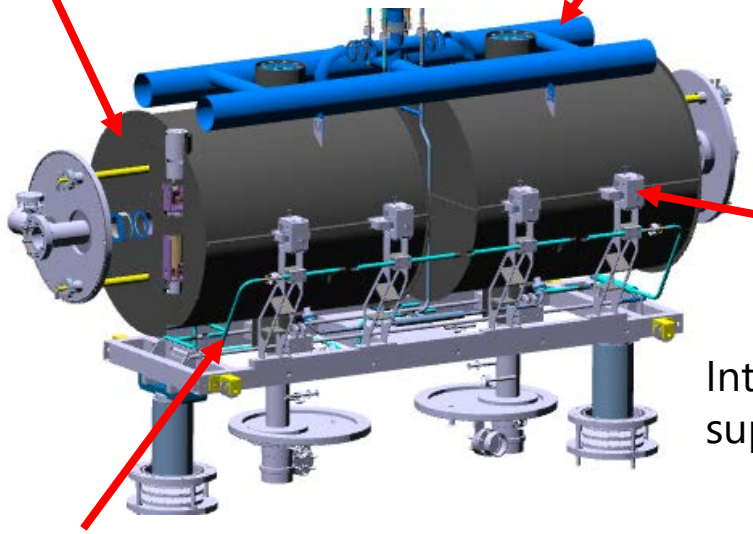
Low-beta Cryomodules

Prototype and series

Prototype Cryomodule
(MAX project design 2018)



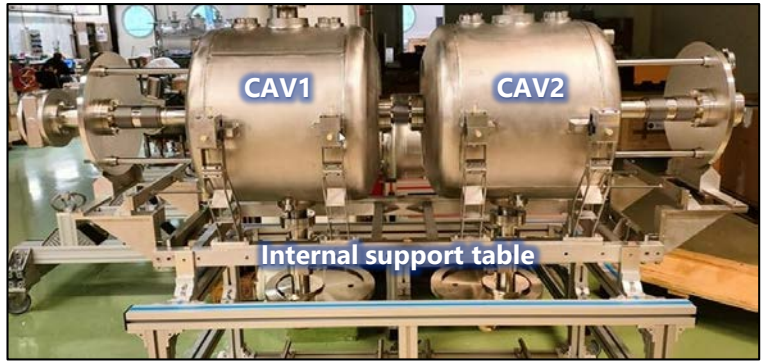


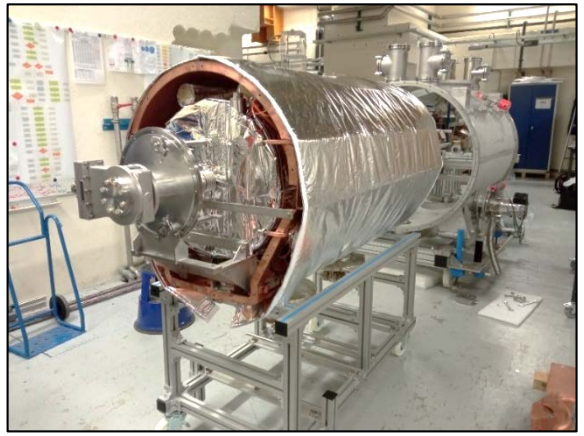


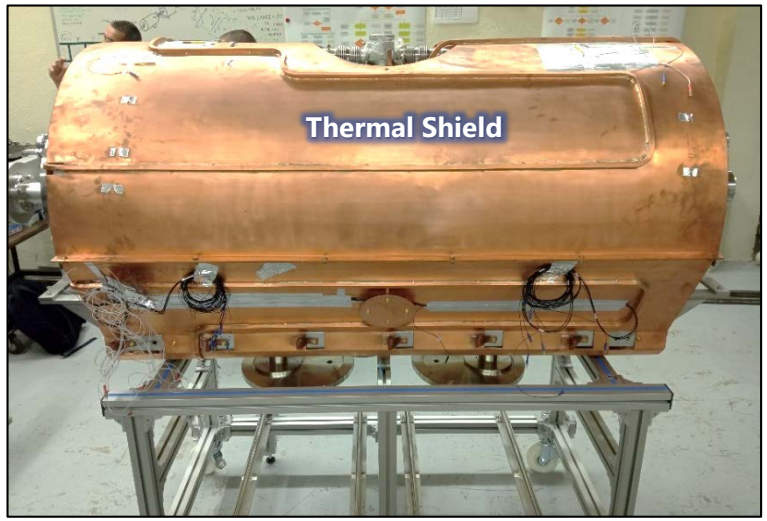
Prototype Cryomodule
(MAX project design 2018)

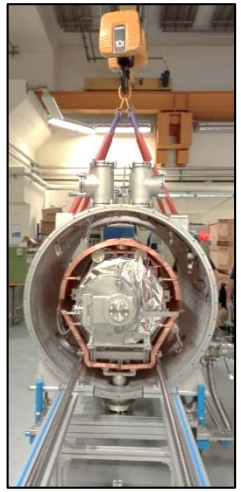
Fotos courtesy of IJCLab and ACS

Prototype cryomodule for MINERVA





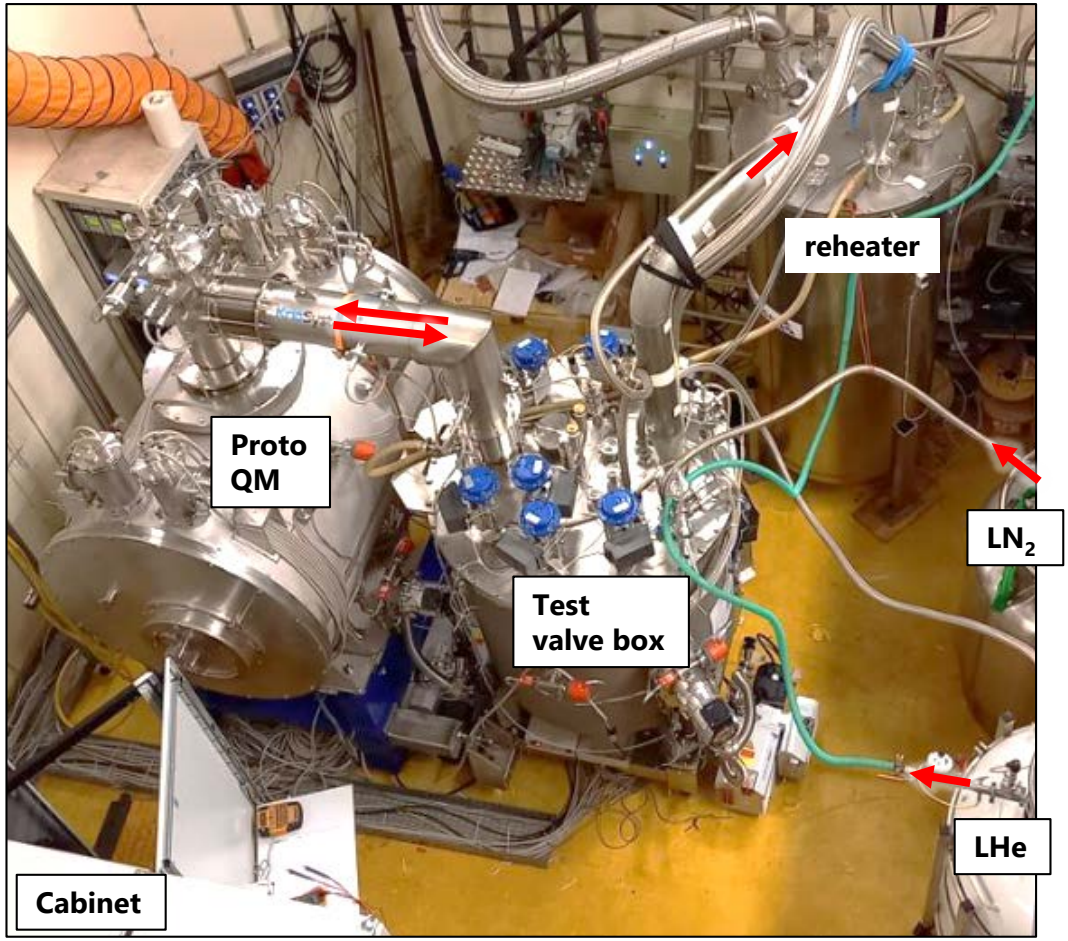




Cryomodule fully assembled in 2022

- Valuable return of experience (assembly sequence, etc…)

Test campaign at IJCLab



Test campaign 2023

- Without RF: done, currently under analysis
- With RF: Starting this week

Series Cryomodule Production

Spoke cavities

- SC spoke cavities adjudicated to Research Instruments (GER)
- **First pre-series cavity** (CAV-LB-03) in surface post-processing flow
- Main post-processing steps achieved successfully
  - BCP (rotary plant)
  - High-pressure rinsing
  - High-temperature heat treatment

research instruments

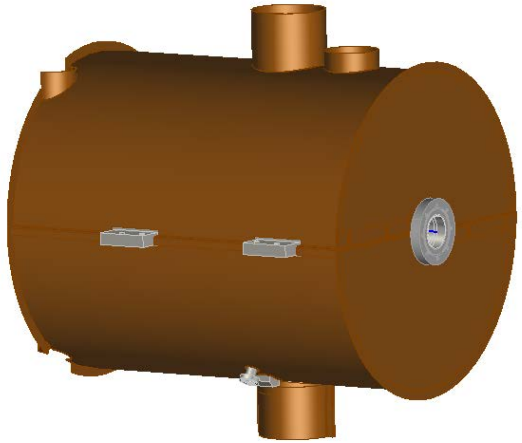
First pre-series cavity

Internal spoke contour

Cavity inside helium tank

Magnetic shield

- Magnetic shields adjudicated to MECA Magnetic (FR)
- Series production started (kick-off Jan-2023)



MECA MAGNETIC magnetic shielding

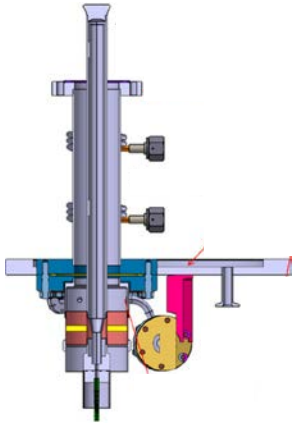
Series Cryomodule Production

- Design consolidation is ongoing for the remaining cryomodule components
  - RF power coupler
  - Cold tuning system
  - Cryostat
- The mechanical design of the valve box is ongoing

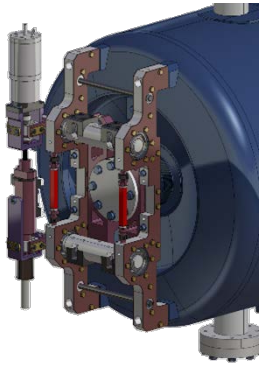
- Example of current activities
  - Implementation of latest return of experience
  - Cross-checking design and performance requirements
  - Update of 3D models and integration check
  - Preparation of tender documentation

- All components will be tendered based on detailed 3D models. The manufacturing drawings are to be prepared by the supplier.

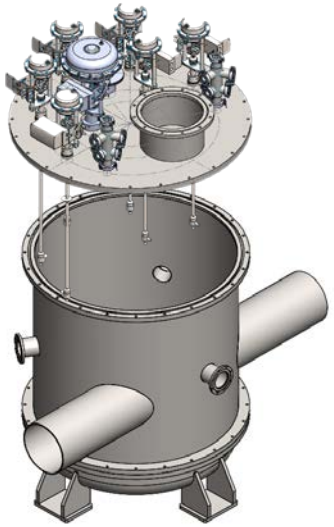
Components under design consolidation in view of call for tender



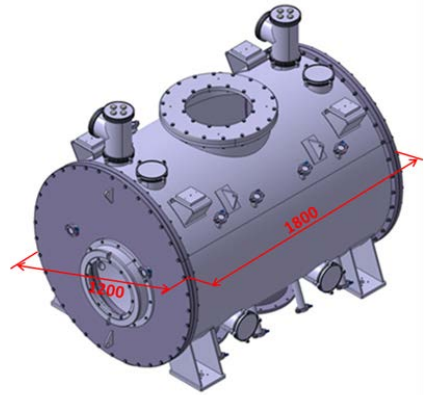
RF power coupler



Cold tuning system



Valve box



Cryostat

Summary

of MINERVA cryomodules and associated cryogenic system

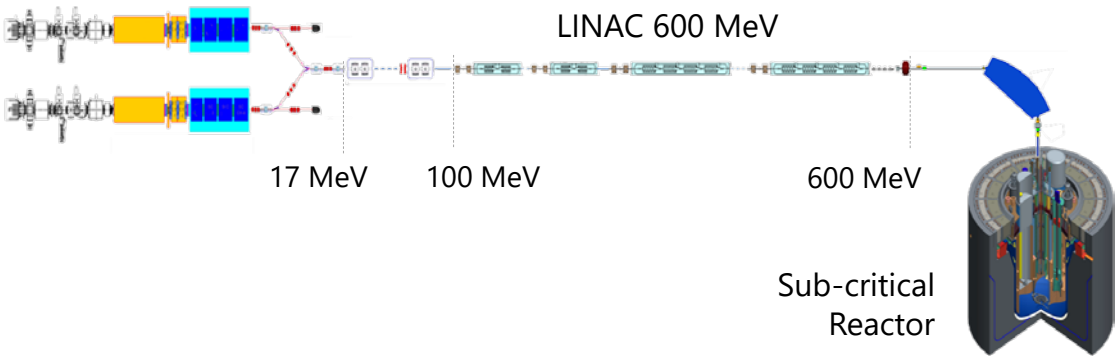
Summary

MYRRHA

- Accelerator Driven System (ADS) comprised of **600 MeV linac** and **subcritical reactor**
- Key use case is **Partitioning & Transmutation** of nuclear waste
- Reliability: MTBF > 250h for beam trips over 3s

MINERVA = MYRRHA Phase 1

- Proton linac, **100 MeV**, 4mA, CW
- 30x identical **cryomodules**, with 2x **spoke cavities** each. Nominal operation at **2 K**
- Beam on **2027**



Low-beta Cryo-Cell (=Cryomodule + Valve Box)

- $\dot{Q}_{2K}$= ~20W (40% dyn)
- $\dot{Q}_{Total}$ = ~80W @ 4.5K equivalent (without margin)

Main cryo activities for 2023

- **Prototype tests** for cryogenics and RF systems
- **Series production** of cavities and magnetic shields
- **Design consolidation** in view of **call for tender** for the remaining components
- **Conceptual design** of Cryoplant + Distribution

Prototype Cryomodule

Series Spoke Cavity

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