MYRRHA phase 1

MINERVA

The MYRRHA-Accelerator Driven System and its accelerator

Ulrich Dorda

03.04.2025, GSI

SCK CEN

- The Belgian Nuclear Research Center
- 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)
  - …
- ≈ 4h drive from GSI

Background on nuclear reactors

- IPCC, IAEA, IEA: Nuclear energy crucial part for CO_2 neutrality by 2050

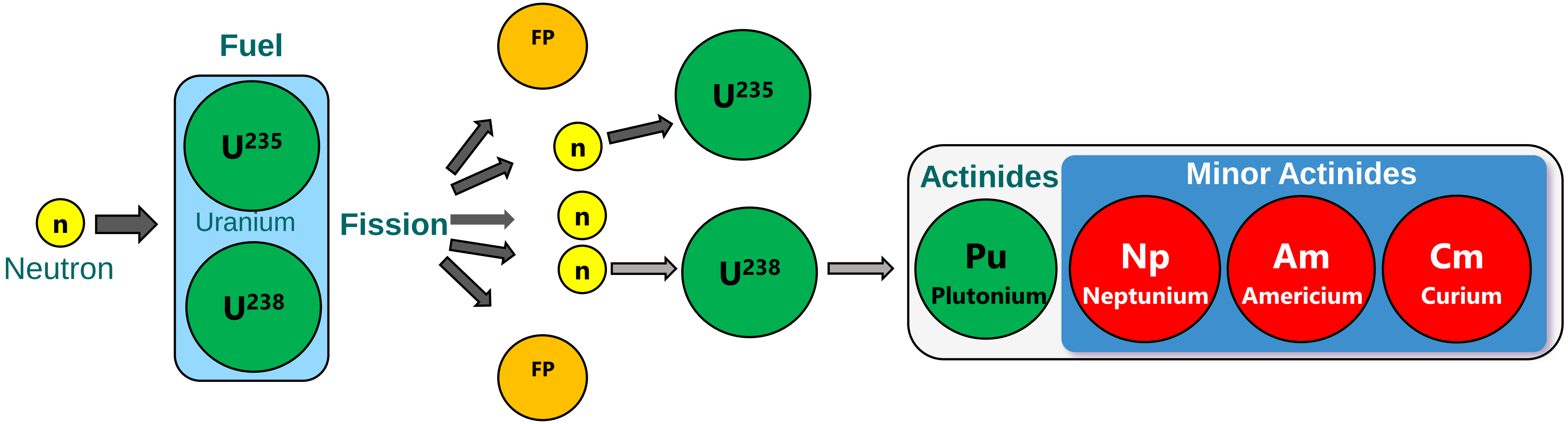
- End 2023:
  - 417 reactors in operation in 31 countries
  - 58 reactors in construction
  - Electricity contribution: worldwide ≈10%, USA: ≈19%, EU: ≈25%, BE: ≈48%

- Nov’23 at COP28: 22 countries commit to nuclear energy in their energy mix
  - x3 installed nuclear power by 2050
  - Confirmed by 36 countries at the Nuclear Energy Summit 2024 (March 2024)

The issues of nuclear reactors

- Nuclear waste with very long half-life
- Critical operation (chain reaction)
- Weapon capable material
- Limited natural resource of fuel

Fission generates high level radioactive waste



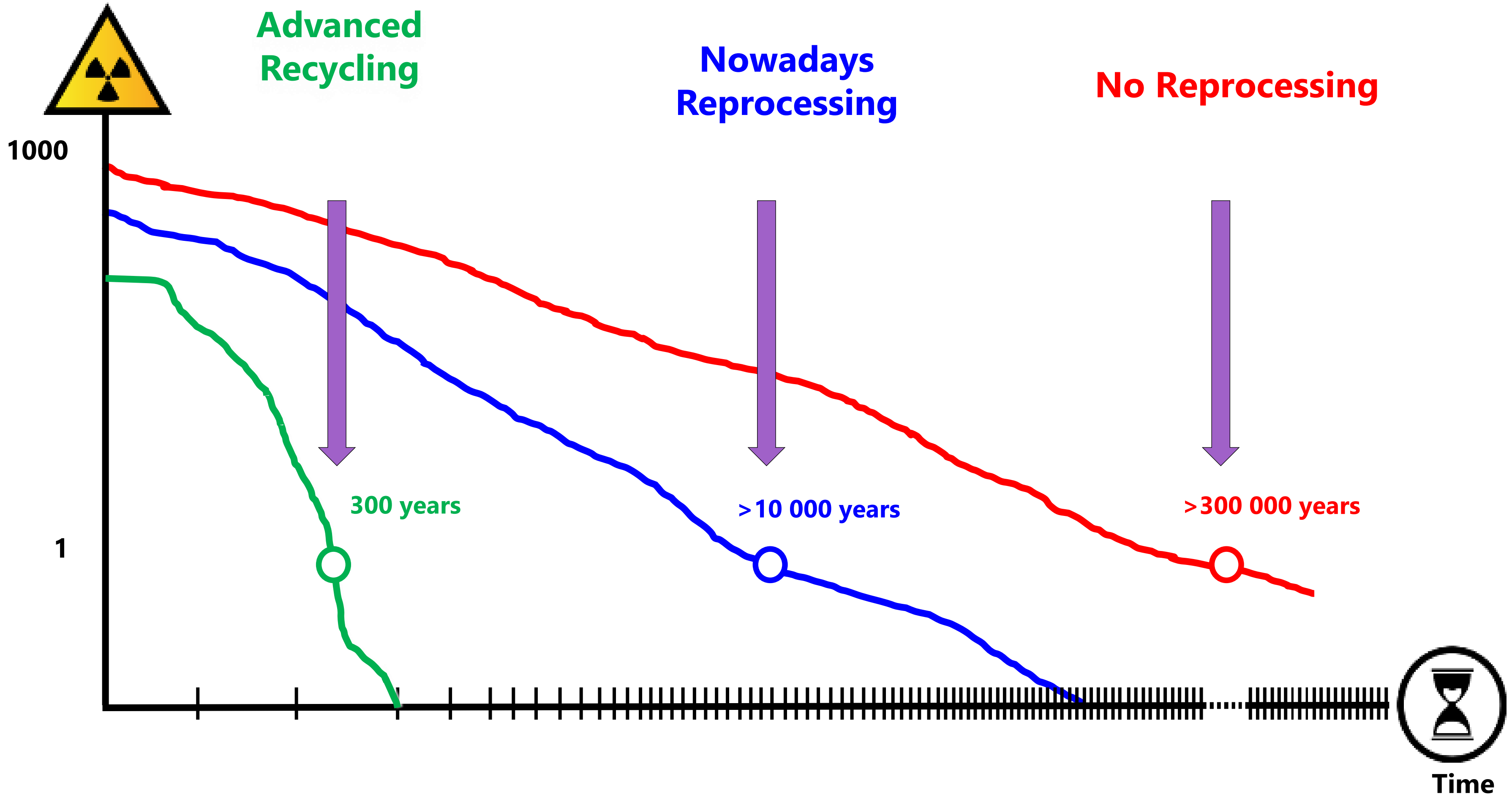
1 ton fuel = electricity for 100,000 Belgian families for 4.5 years

➔

Spent fuel contains:

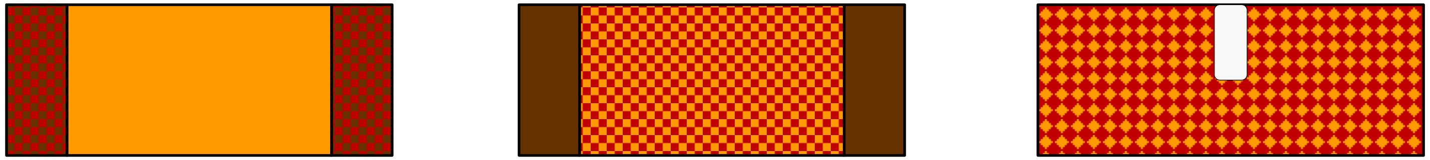
- **94,7% of resources we can recycle (U+Pu)**
- **5,1% of nuclear waste with low radiotoxicity (FP's)**
- **0,2% of high radiotoxicity nuclear waste**

Transmutation



Three options for Minor Actinide (MA) transmutation

Fast Reactor heterogeneous	Fast Reactor homogeneous	ADS



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

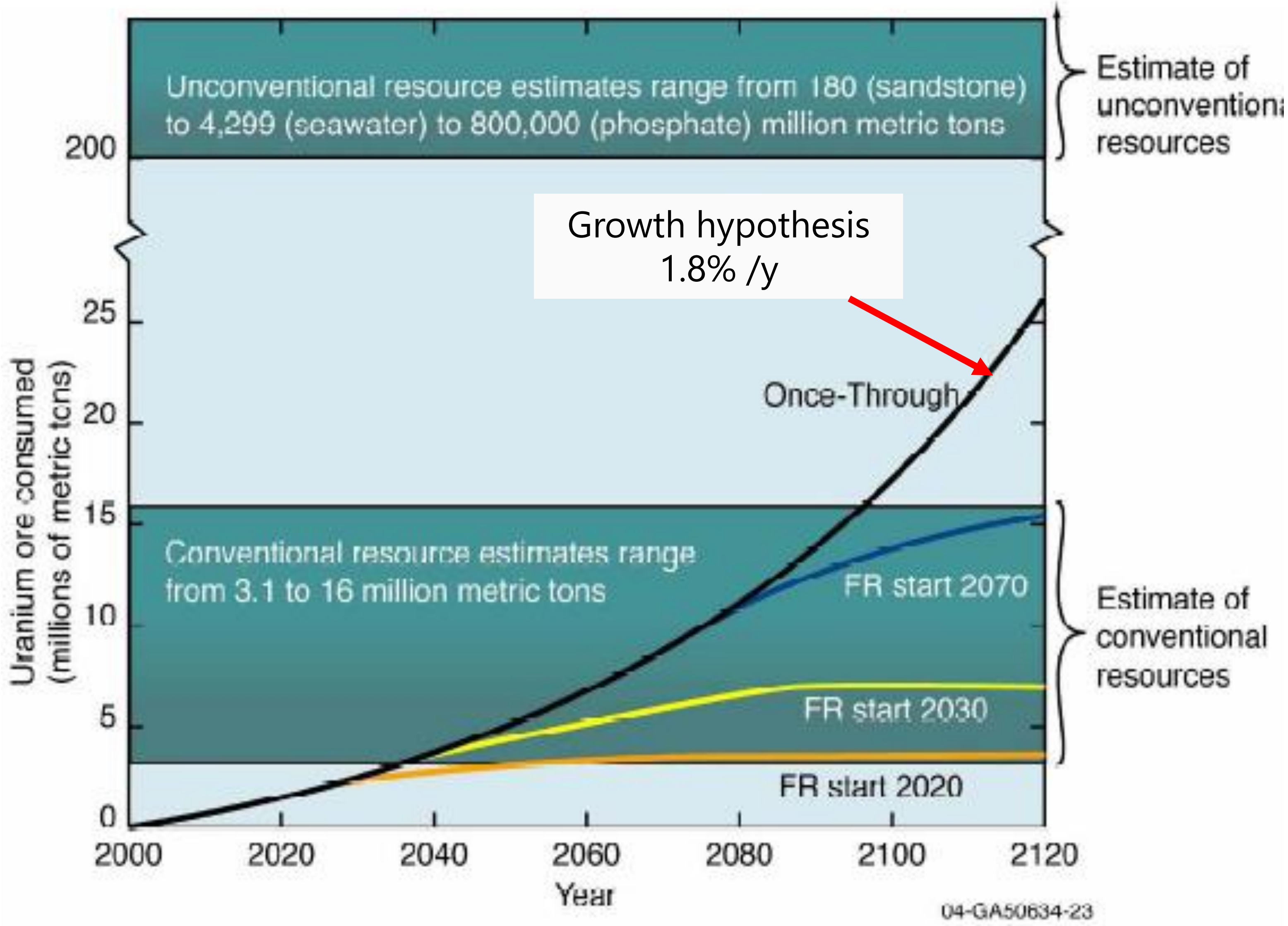
Transmutation rates:
Fast Reactor: 2 to 4 kg/TWh
ADS[1]: 35 kg/TWh
(Core safety limits amount of MA in a critical core for transmutation)

Fast Reactor: fission chain reaction sustained by fast neutrons >1 MeV

1) 400 MWth EFIT design

ISC: Restricted

Resource usage



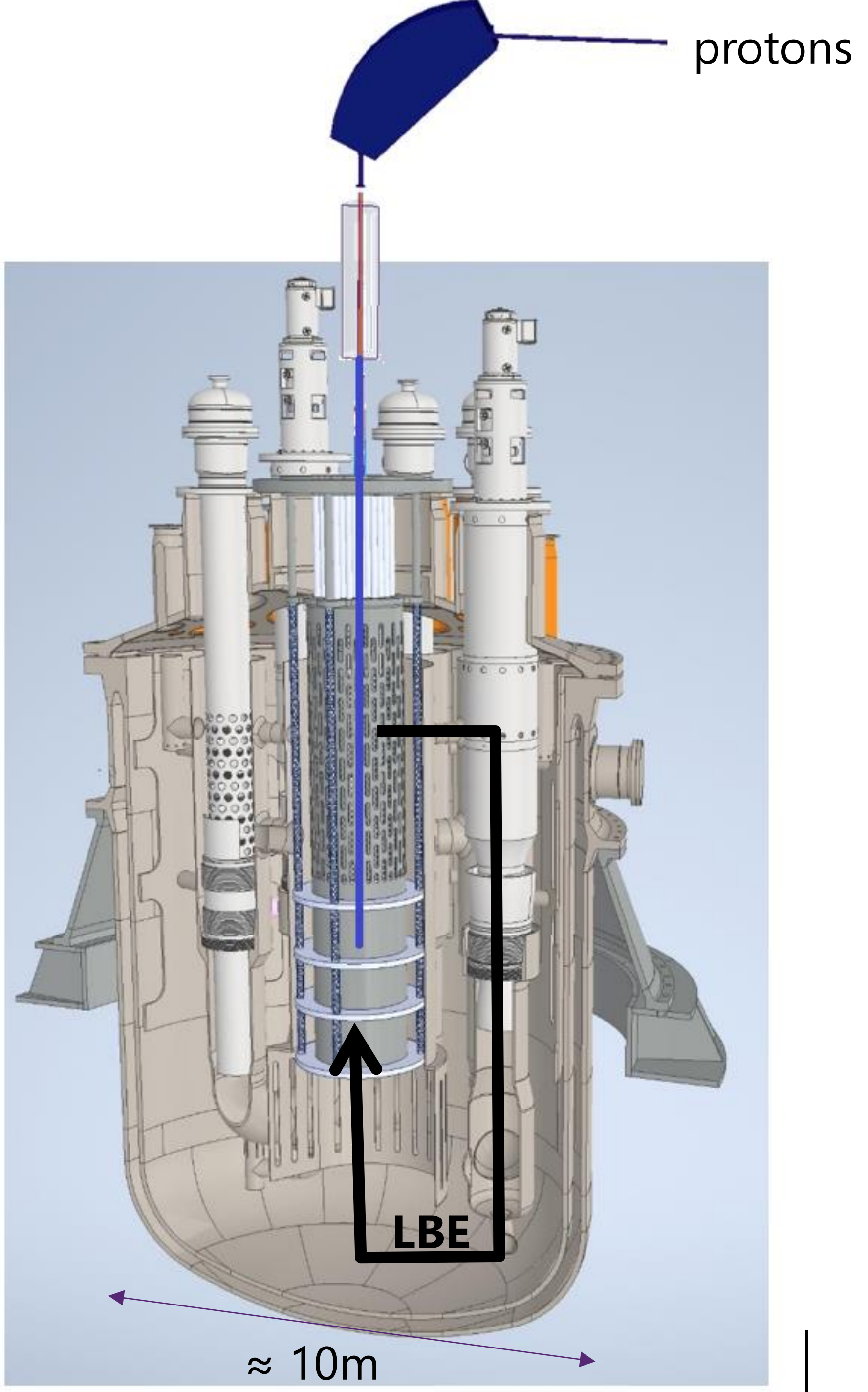
US DEO projection

Inherent safety

- Subcritical reactor – the ACC stops, the reactor "stops"

MYRRHA Reactor

Parameter	Unit	Value
Maximum core power in critical configuration	MW_{th}	63
Maximum core power in sub-critical configuration	MWth	55
LBE flow rate	m/s	2
Core height	M	1
LBE core inlet temperature	C	220
Spallation target temperature	C	450
LBE core out temperature	C	380
Final proton beam drift length	m	12



Other:

- Beam line must be removable
- Beam line must not create radiation above reactor

ACC requirements

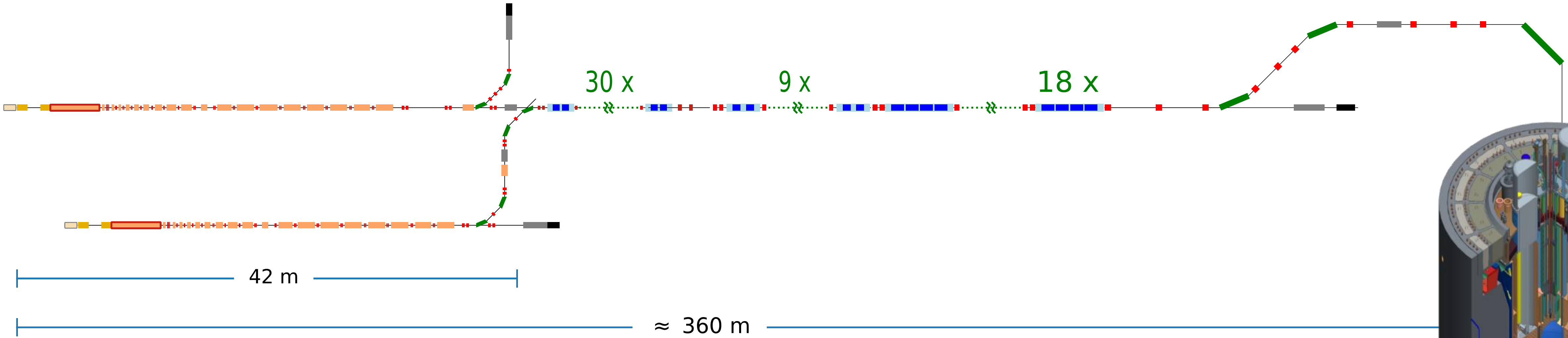
- Protons
- > 500 MeV
- MW class average beam power
  - mA CW beam current
  - duty factor adaptation
- Reactor cycle operational schedule
  - MYRRHA: 90 day cycle
  - industrial ADS: quasi continuous
- High reliability
  - no beam interruption > few s
  - to avoid thermal stress on reactor components
- High availability
  - To get uptime
- Cost/Energy efficiency (CAPEX/OPEX)
  - Industrial approach

Options & worldwide efforts

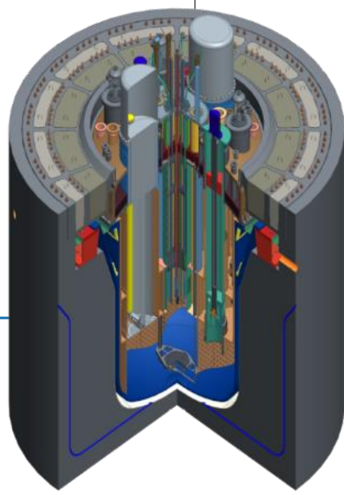
- SC-Linac:
  - **MYRRHA – 1st stage (100 MeV) in implementation**
  - **CiADS – in implementation**
  - JADS – design study
  - …
- Cyclotron
  - Transmutex company – design study
  - TEXAS A&M university – design study for stacked cyclotrons
  - ….

Purpose:

- ADS technology demonstrator at pre-industrial scale
- Flexible irradiation facility (Radio isotope production, reactor fuel research, …)



600 MeV Protons, 4mA - CW
3 types of SC-cavities



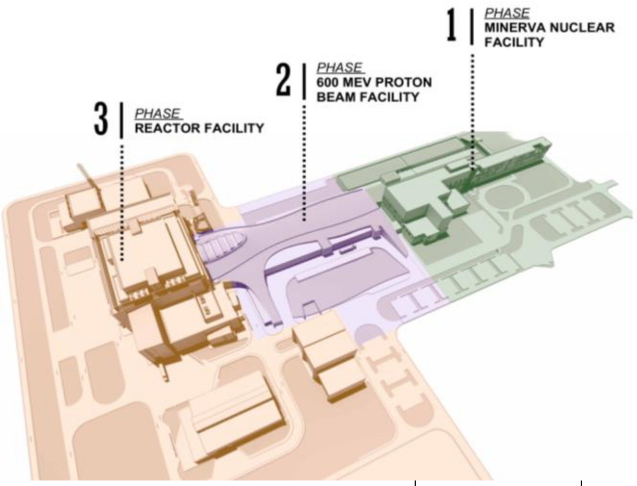
SUBCRITICAL REACTOR (~70MWTH)

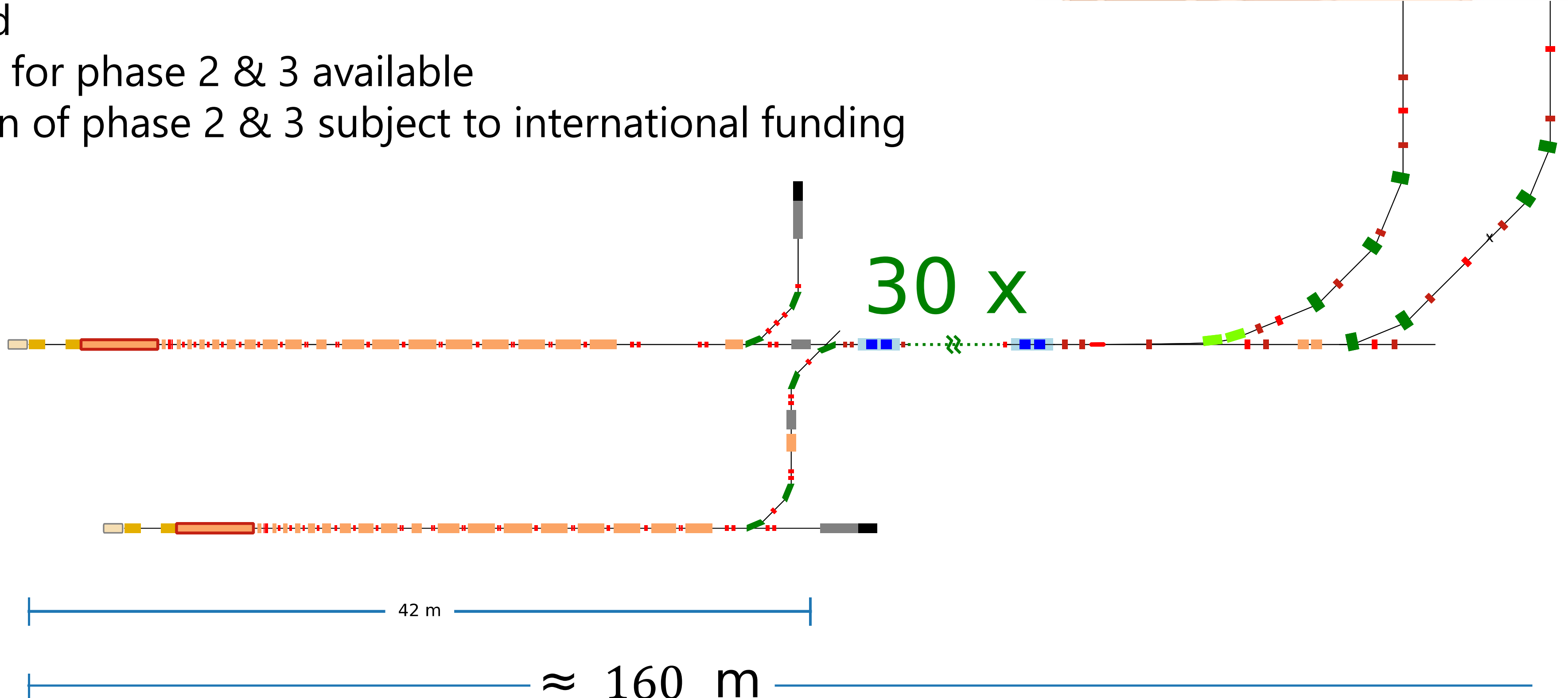
2018: Belgian government decision on MYRRHA

- Belgium decides **to build MYRRHA**, a new large research infrastructure in Mol
- Belgium decides **to establish a non-profit organization MYRRHA IVZW/AISBL**
  - in charge of the MYRRHA facility international outreach and serving as the legal structure for welcoming international partners
- Belgium decides **to establish governmental support** for promoting MYRRHA international partnerships
- Belgium decides to **allocates a budget of € 558 m** towards the **project's <u>phased approach</u>**

MINERVA = MYRRHA phase 1 implementation

- ✓ **<u>100 MeV</u>**
  - ✓ **1 injector**
  - ✓ **1 SC cavity type**
- ✓ **Test the reliability concepts (RF-fault tolerance)**
- ✓ Two target stations:
  - ▪ **ISOL system (PTF)**: *reduced duty factor (50kW)*
  - ▪ **Full power Facility (FPF)**: *Fusion material research, 400 kW*
- ✓ Spreading the investment costs
  - ✓ Phase 1 funded
  - ✓ Funds for R&D for phase 2 & 3 available
  - ✓ Implementation of phase 2 & 3 subject to international funding





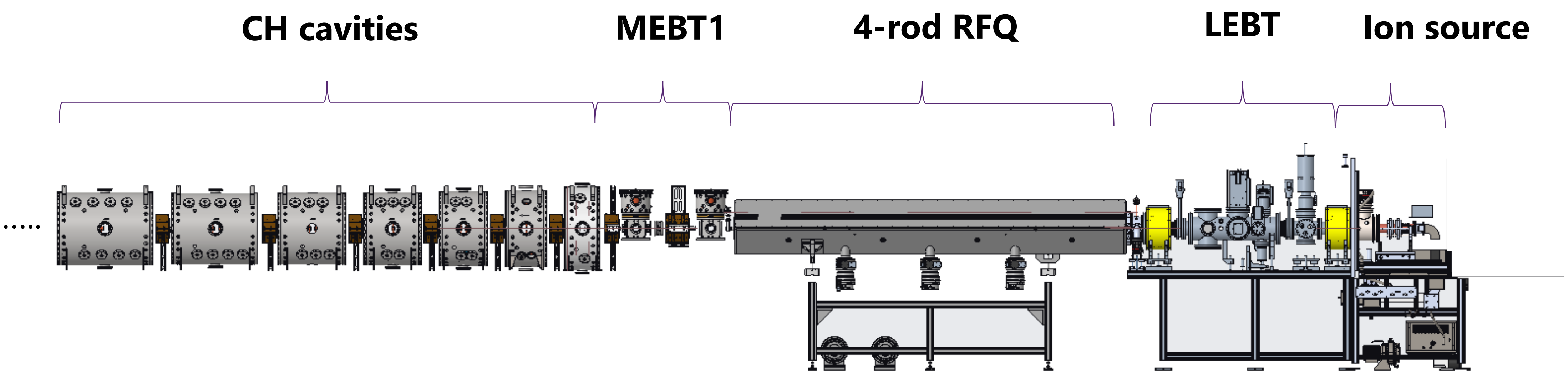
Starting up

- Accelerator team
  - 1st hires on site beginning 2020
  - By now ≈35 persons -> heavily relying on collaborations and industry
  - Multinational with various backgrounds
  - During Corona, at remote location, unknown to ACC-community

- Critically reviewed the pre-existing designs
  - Significant rework needed on layout, beam optics, operational concept, component designs, …

- Nuclear license was approved by FANC in Nov. 2022

17 MeV Injector

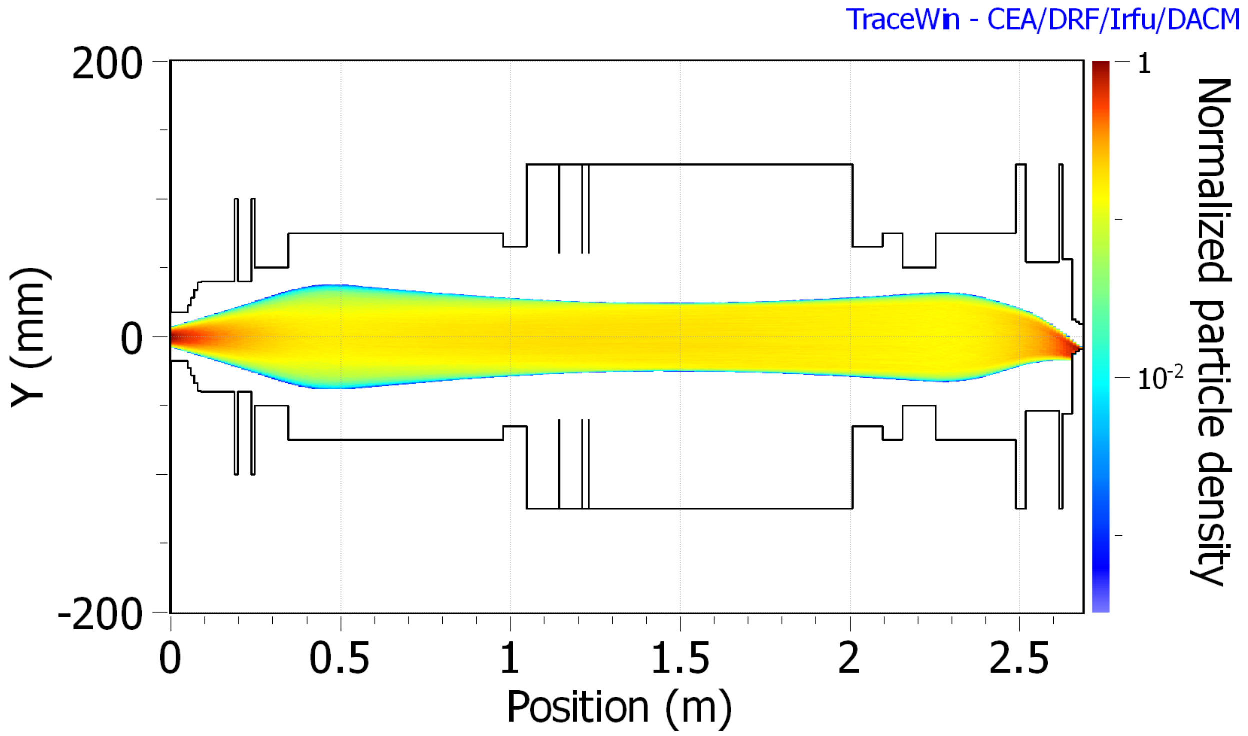


176 MHz normal conducting RF
- 4-rod RFQ with up to 160 kW to 1.5 MeV
- 2 Quarter-wave resonators
- 15 accelerating + 2 rebunching CH-cavities
- RFQ & Cavity design by IAP/Bevatech
- CH-cavity production started at RI

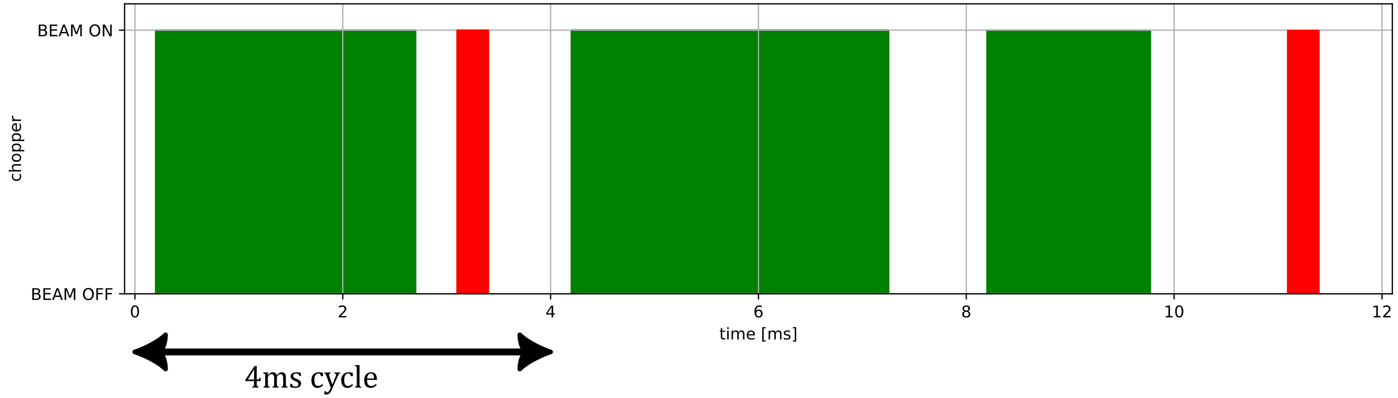
30 keV ECR-DC-proton source (Pantechnik)

LEBT: 2 solenoids, chopper & BD

LEBT

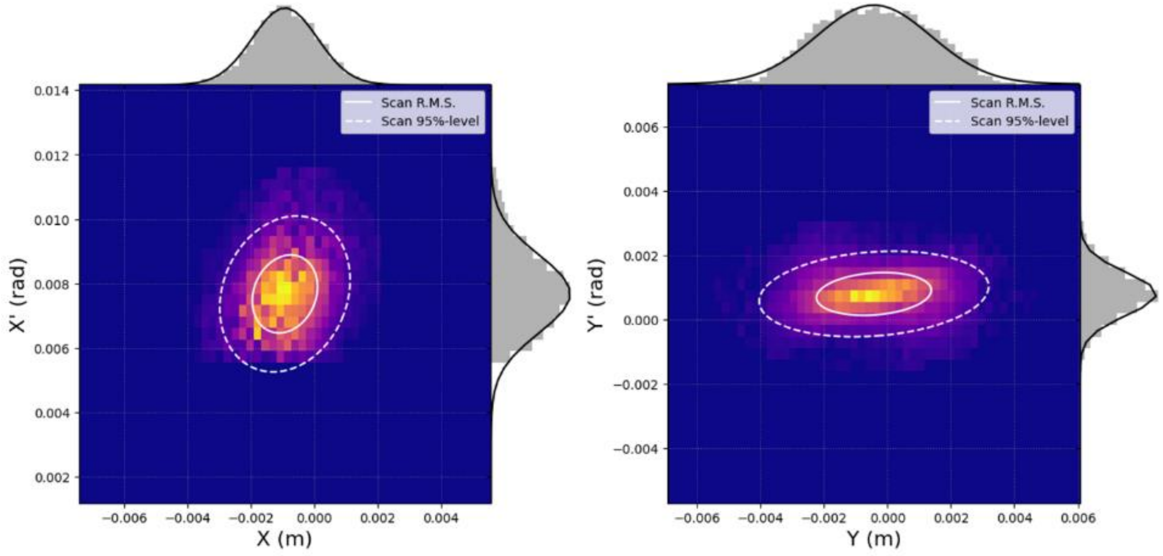


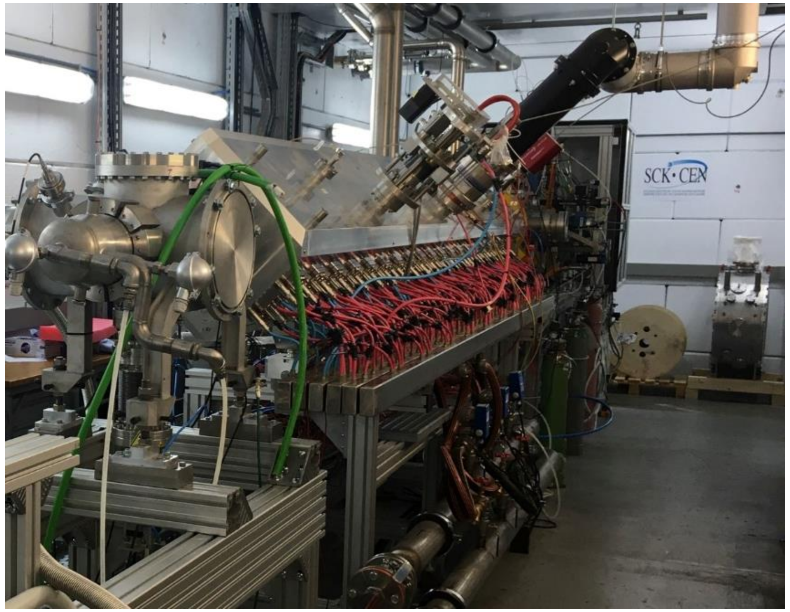
- Need for gas injection for space charge compensation still under investigation. (takes time to build up)
- Electrostatic Chopper defines the macro beam structure: 2 beam destinations within 4ms
- 2 Solenoids
- Allisson scanner



Injector test stand

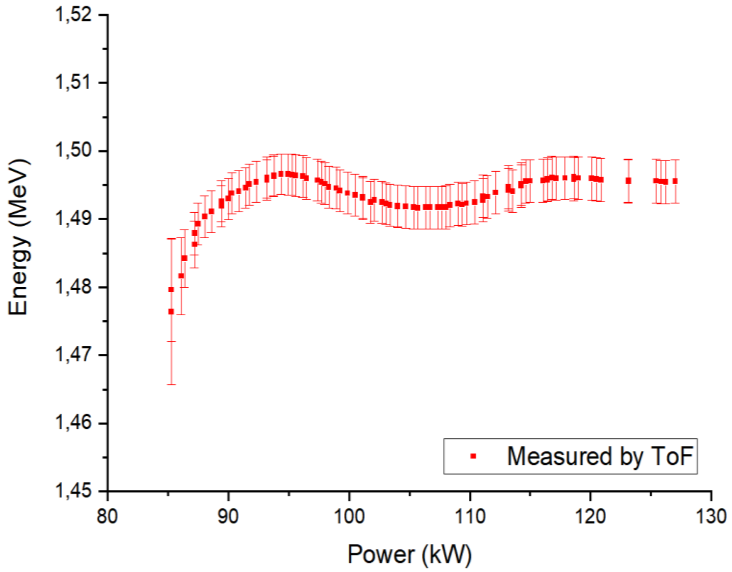
- Experimentally validated up to exit RFQ in R&D manner
- Test stand now dismantled and being completely refurbished/rebuilt



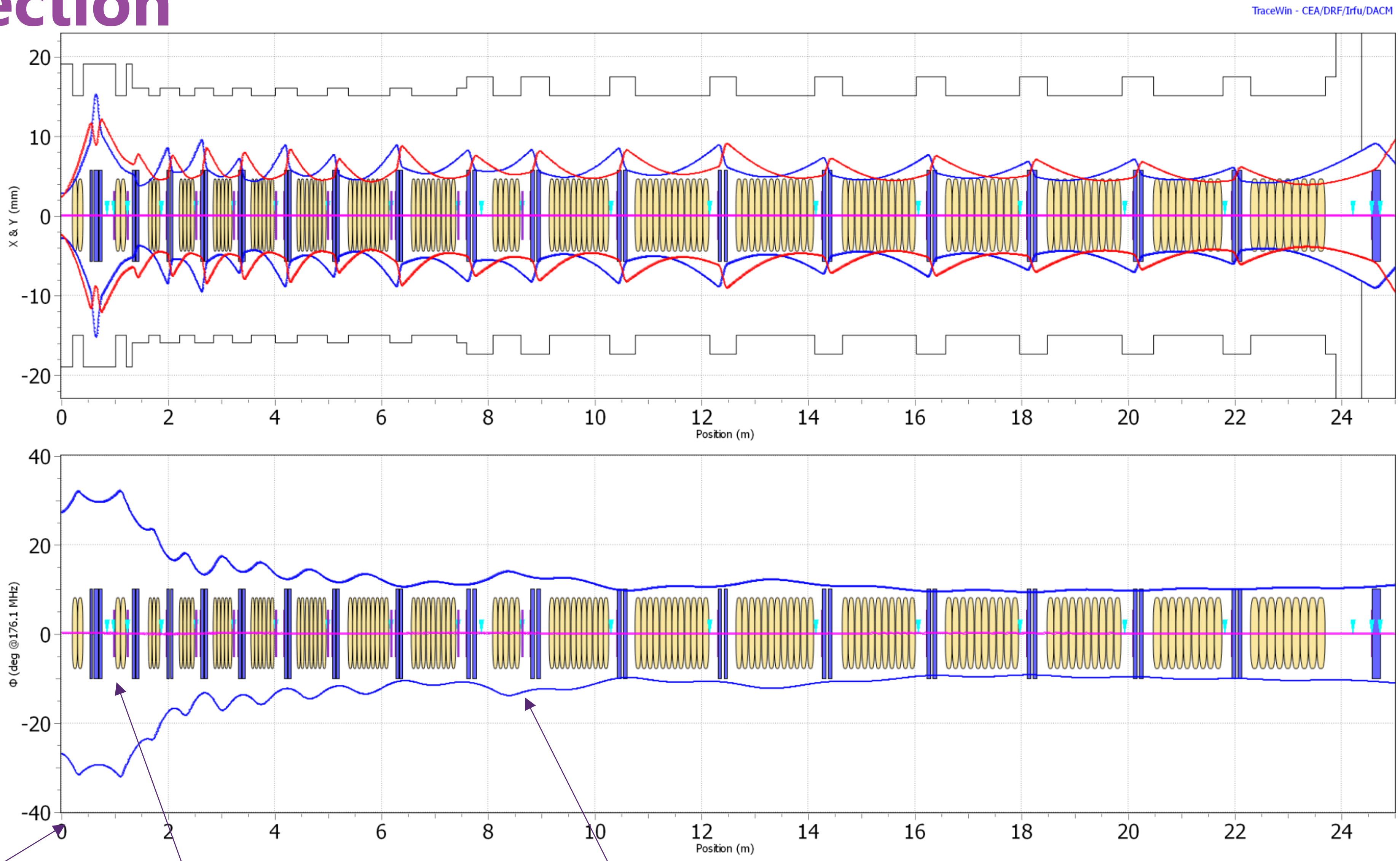


Emittance	Horizontal ($\pi.mm.mrad$)	Vertical ($\pi.mm.mrad$)
Simulation	0.114	0.113
Scan	0.080(7)	0.093(5)

SLIT-GRID measurement after RFQ



CH-section



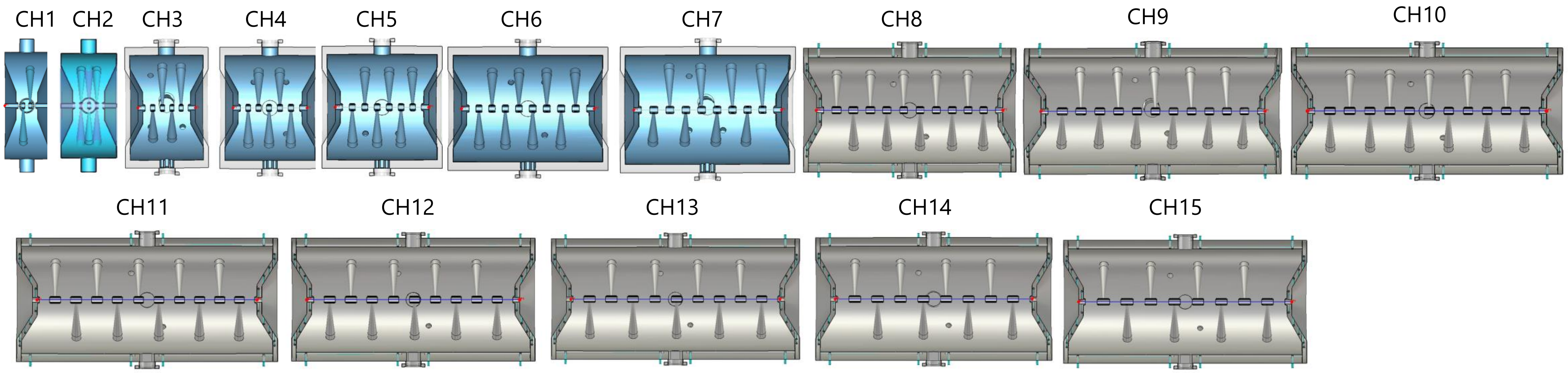
6σ sizes

RFQ exit

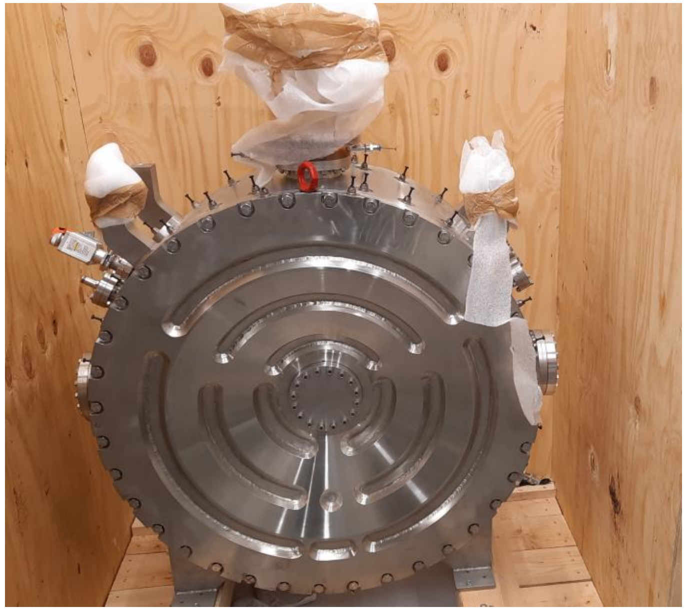
MEBT1: Matching section with 2 quarter wave rebunching cavities

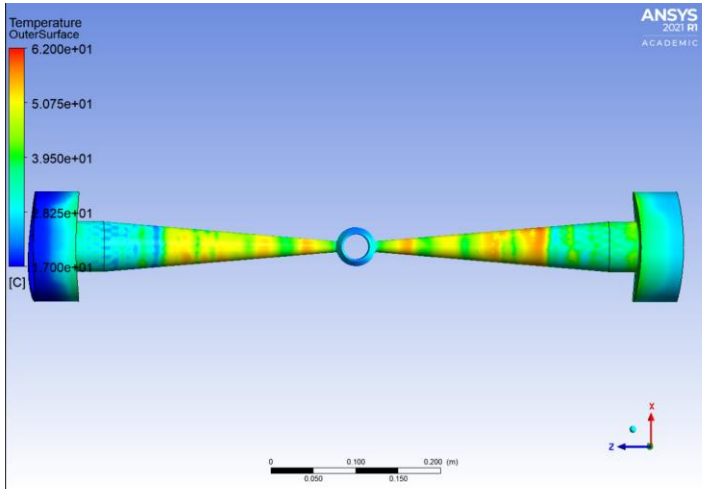
MEBT2: Rebunching with CH-cavity

Crossbar H-mode cavities (CH)



- Up to 40kW RF
- T stabilized to ≈1°C
- Design by IAP Frankfurt
- Production at RI ramping up

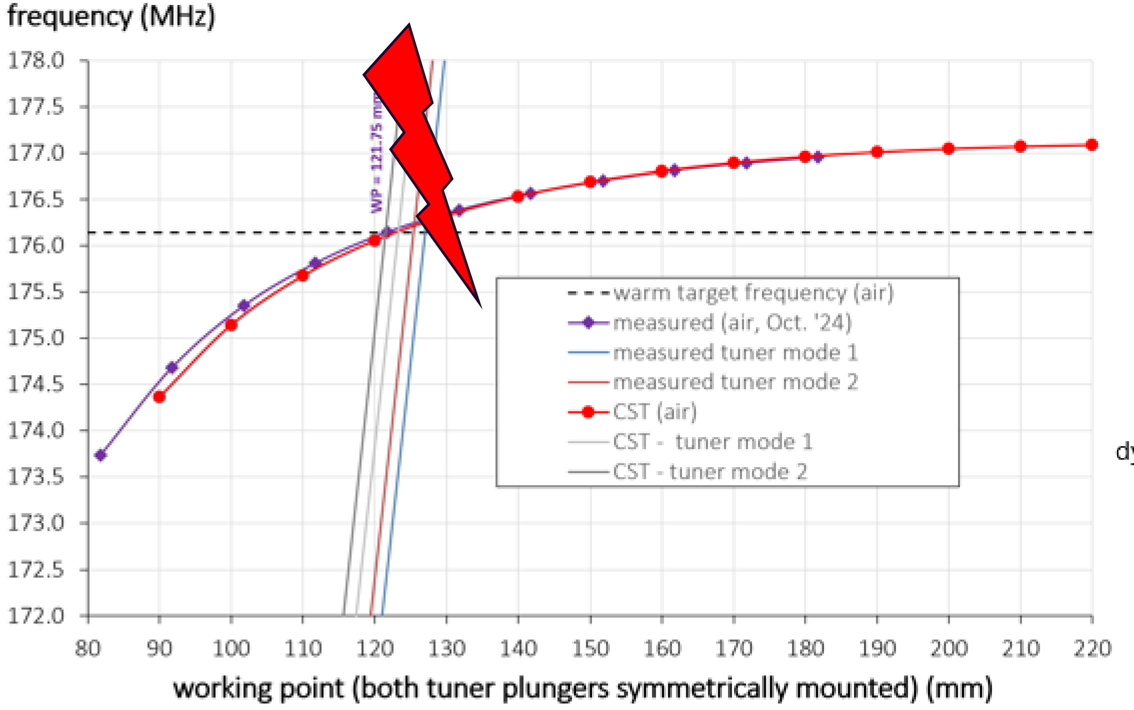




Crossbar H-mode cavities (CH)

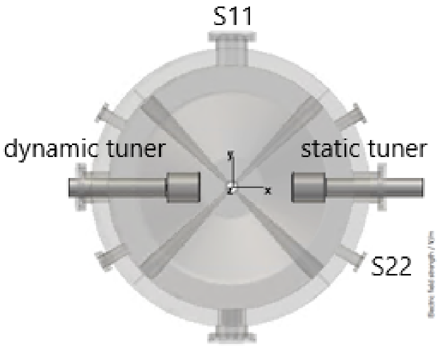
Critical by design and to be verified experimentally
1) Water cooling efficiency, specifically for stems
2) Fundamental mode tuning and avoiding tuner modes

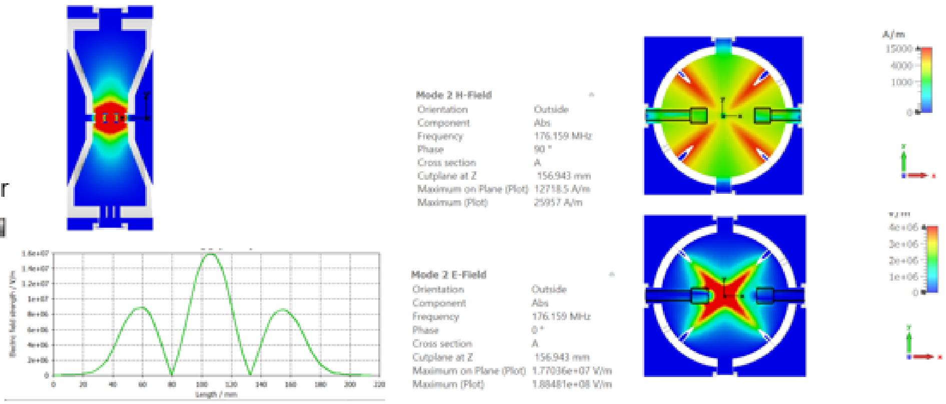
CH-01 measurement



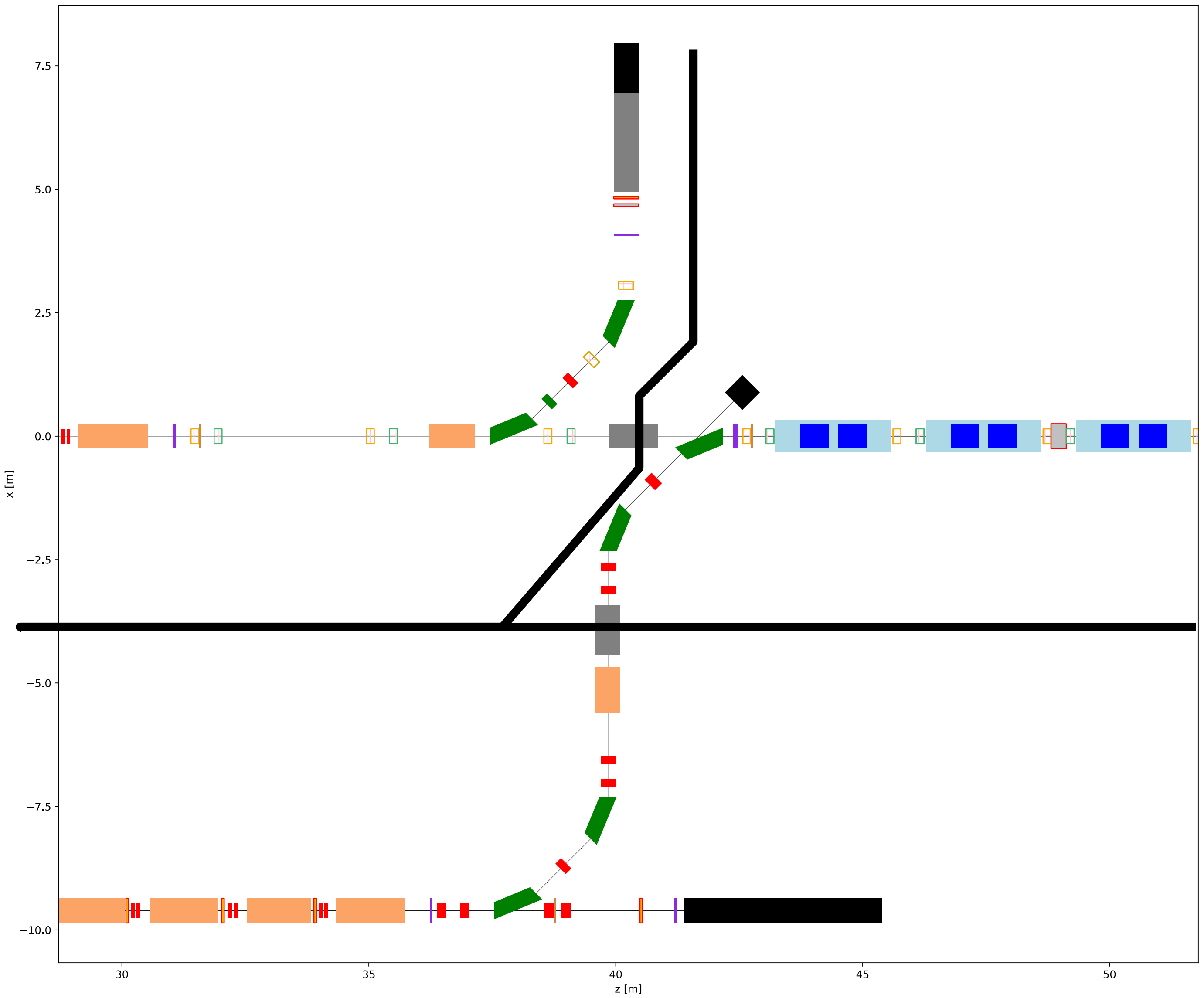
Accompanying CST Simulations

	WP (mm)	f0 (MHz) in air	f0 (MHz) in vacuum	tuner mode measured (MHz)
dynamic tuner	101.25	176.150 (meas.) 176.109 (-50 kHz)	176.200 (+ 50 kHz) 176.159 (sim.)	159.586 (meas.) 161.4 (sim.)
static tuner	191.75			228.128 233.5 (sim.)



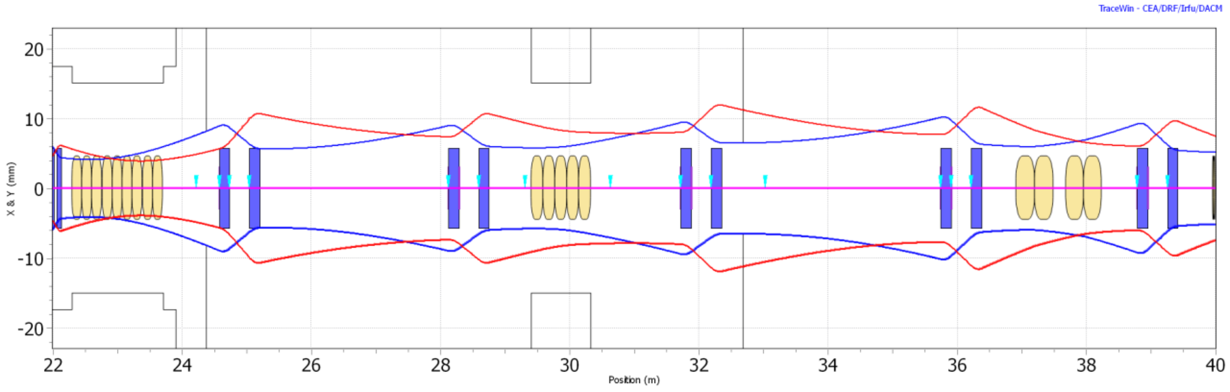


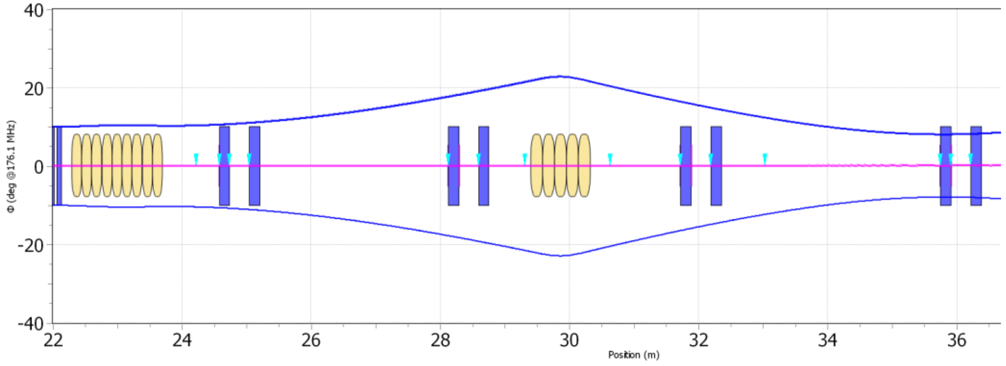
Injector switching and matching sections

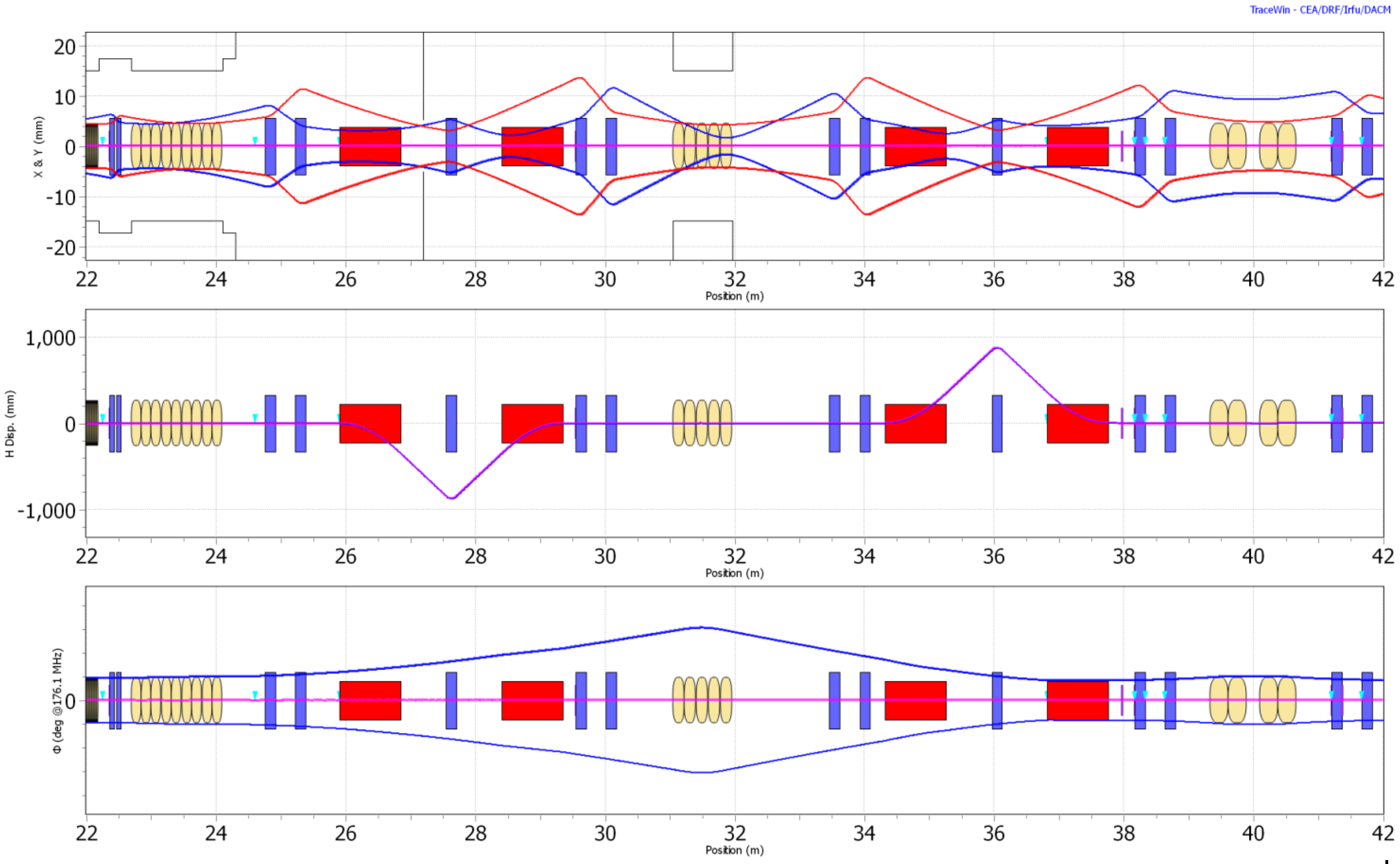


- Includes collimation
- Hot standby injector with full diagnostics e.g. fast faraday cup
- Tuning beam dumps
- MINERVA only with 1 injector (various layout options for upgrading to 2 injectors)

Injector switching and matching sections

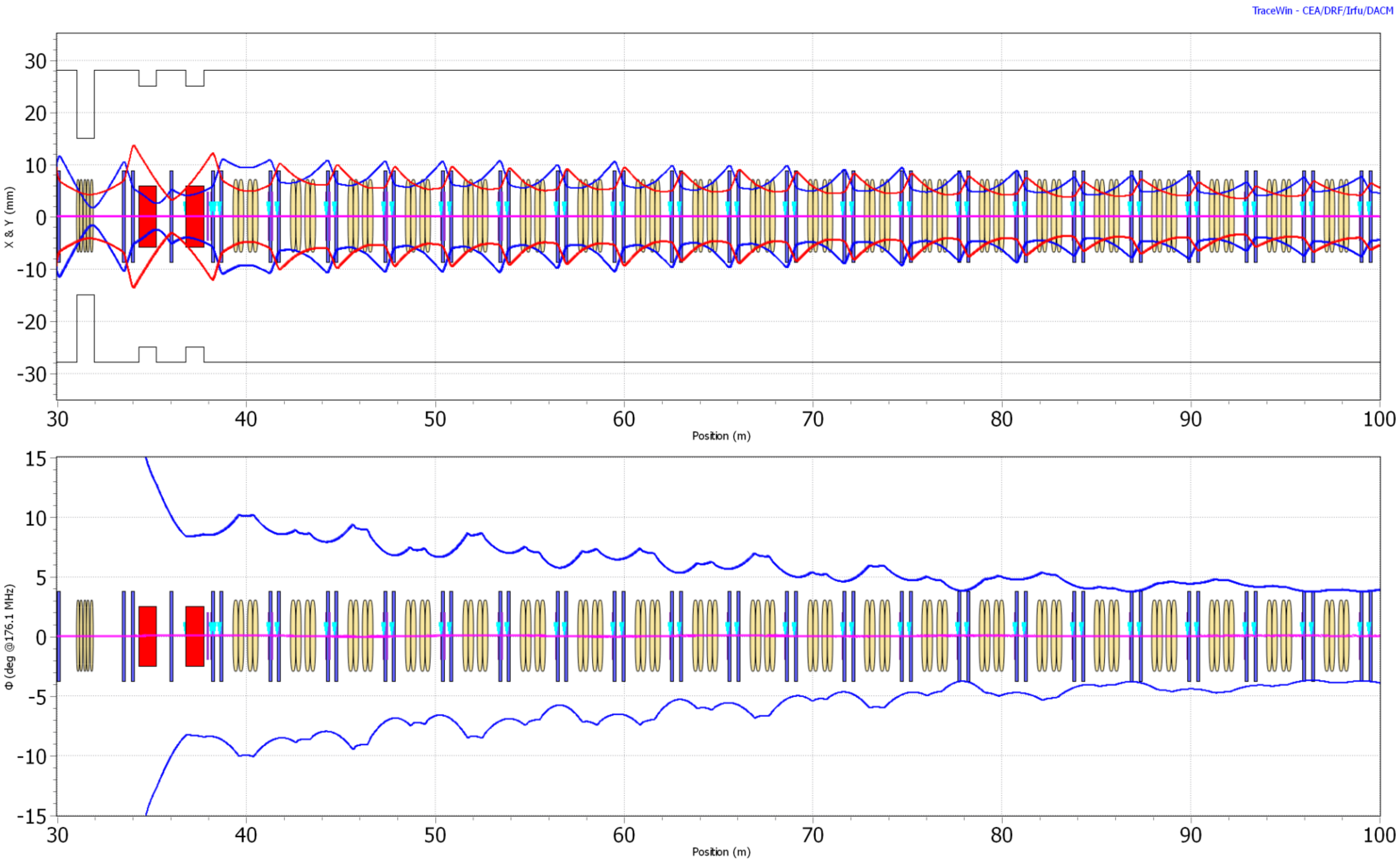






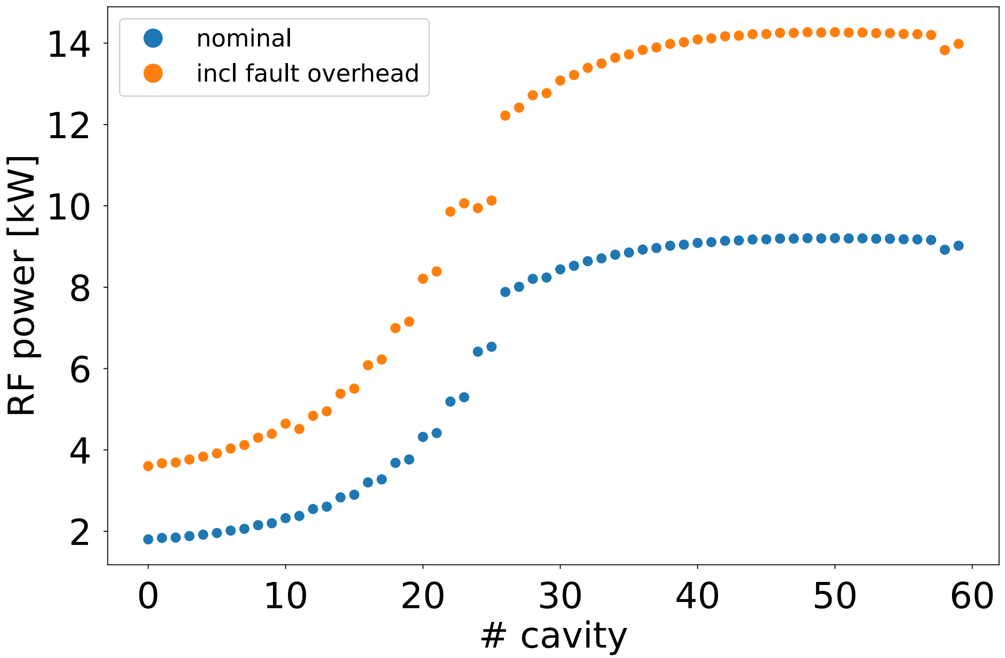
SC-linac

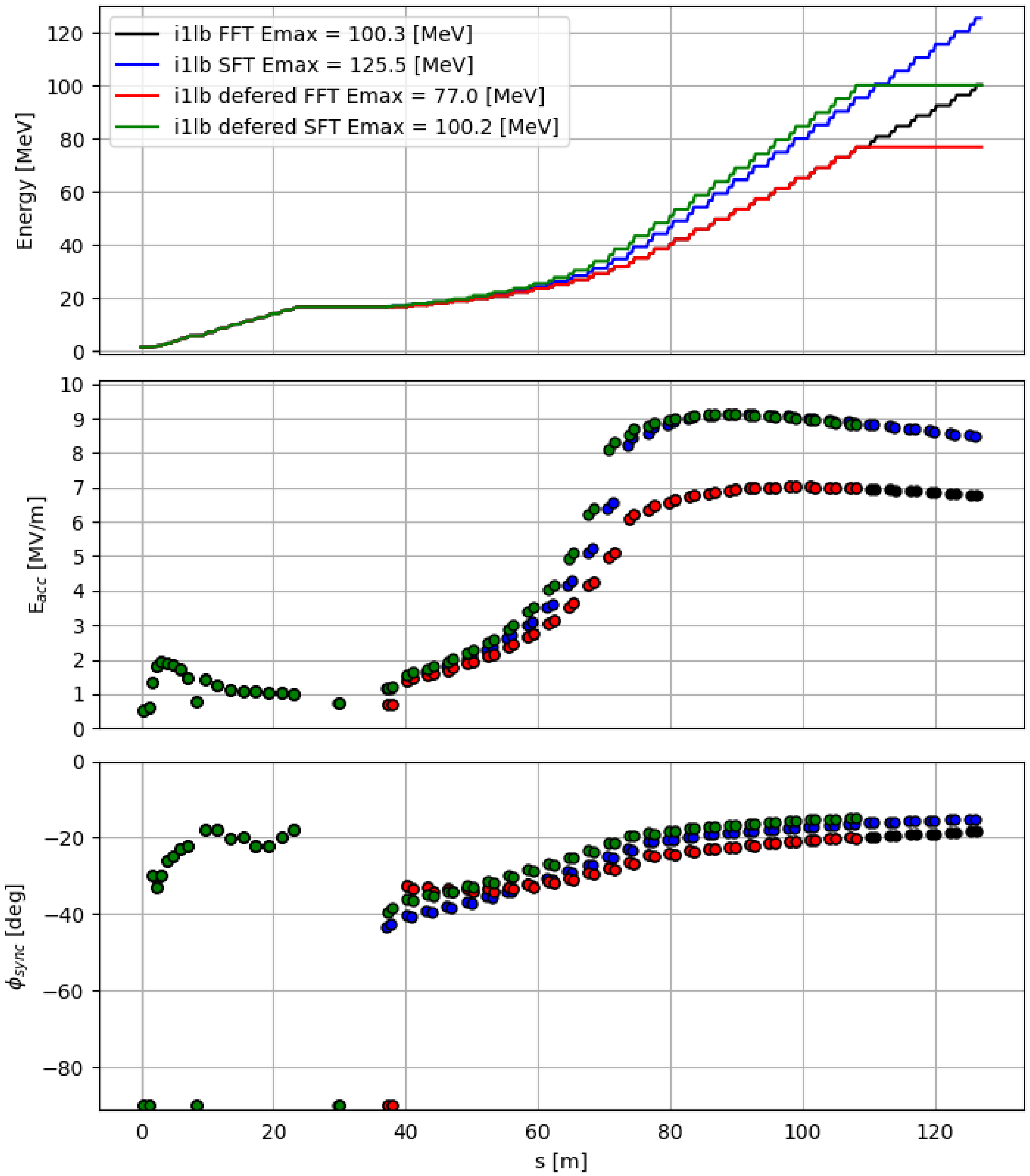
- 30 cryo modules with each 2 single spoke cavities (352.2 MHz, β = 0.352)
  - Initially 24 cryomodules
- Warm section with doublet & diagnostic
- BPM & correctors integrated into quadrupoles



Fault tolerance

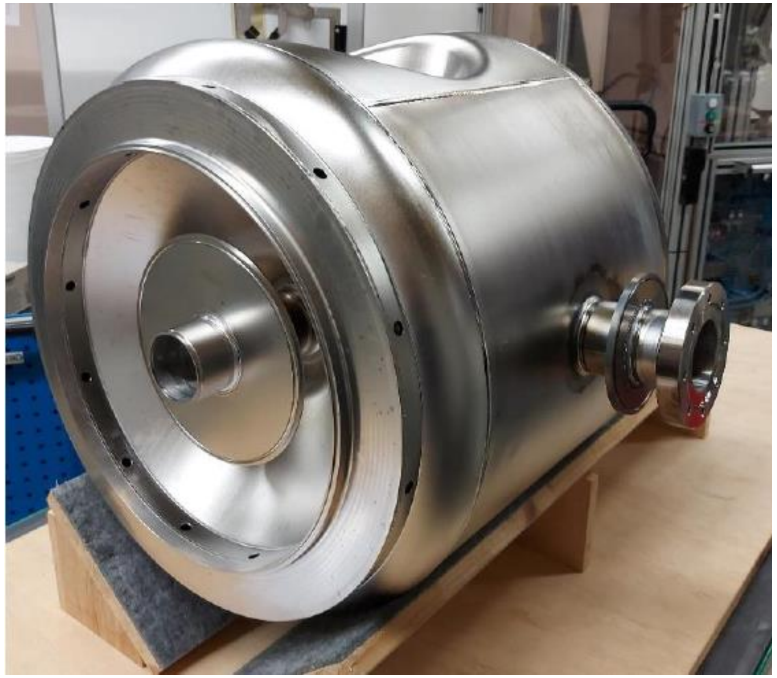
- RF overhead to compensate for failed cavities

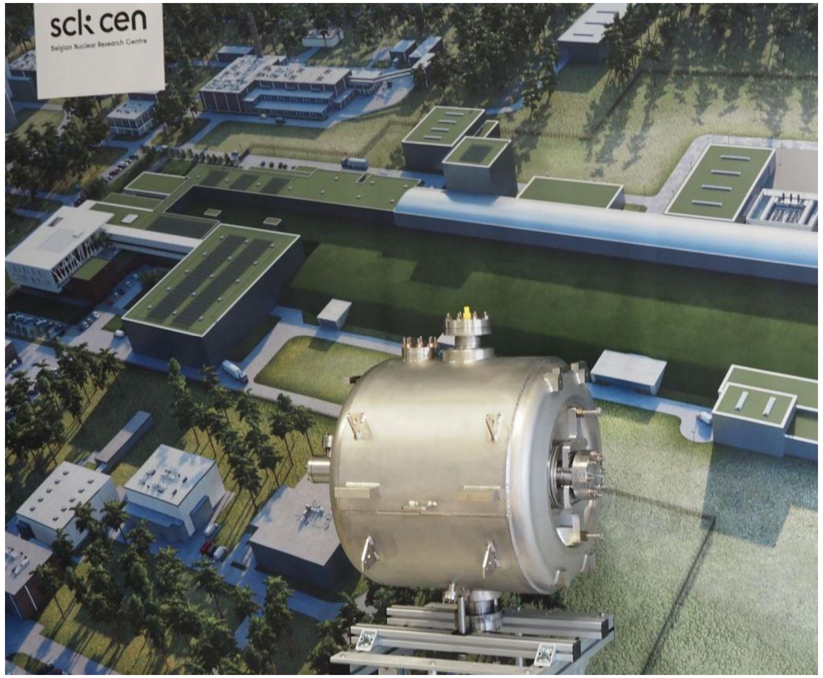




Single Spoke RF cavities

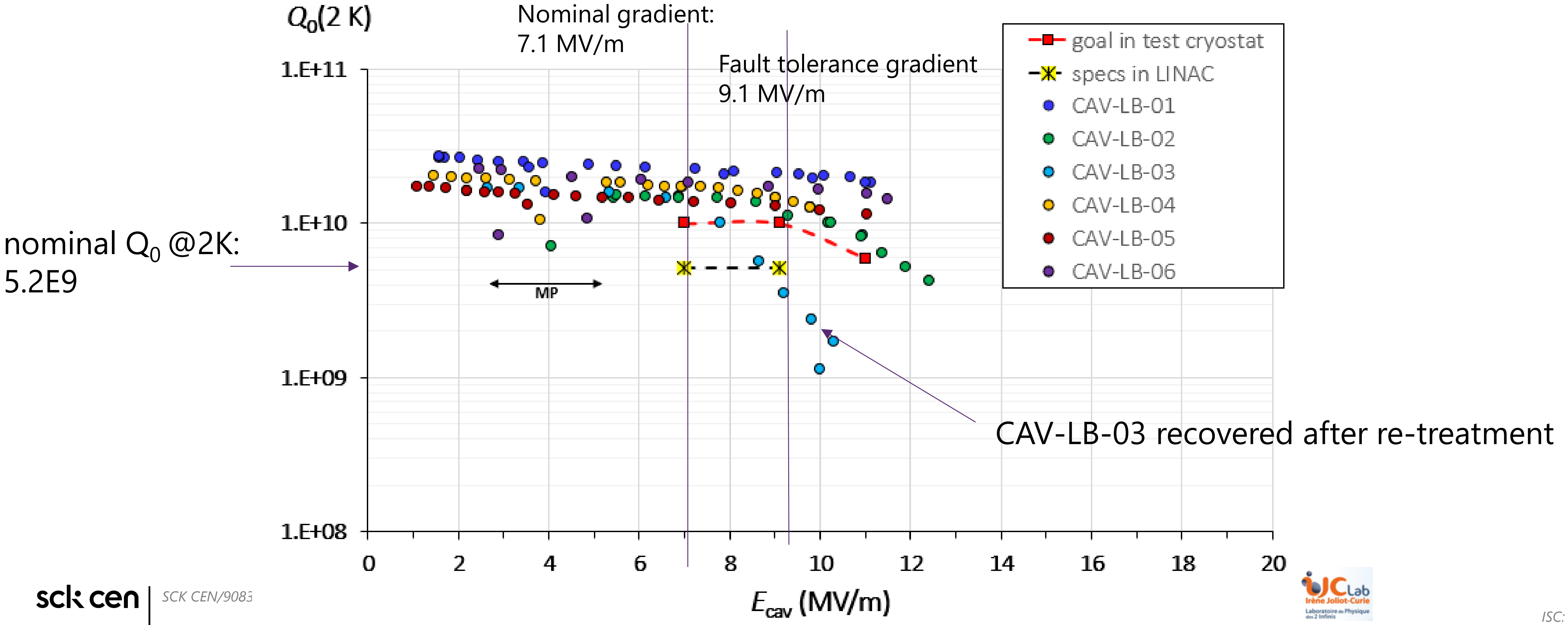
- Two 352.2 MHz single spoke cavities @2K per CM
- Pre-series cavity production completed at RI research instruments



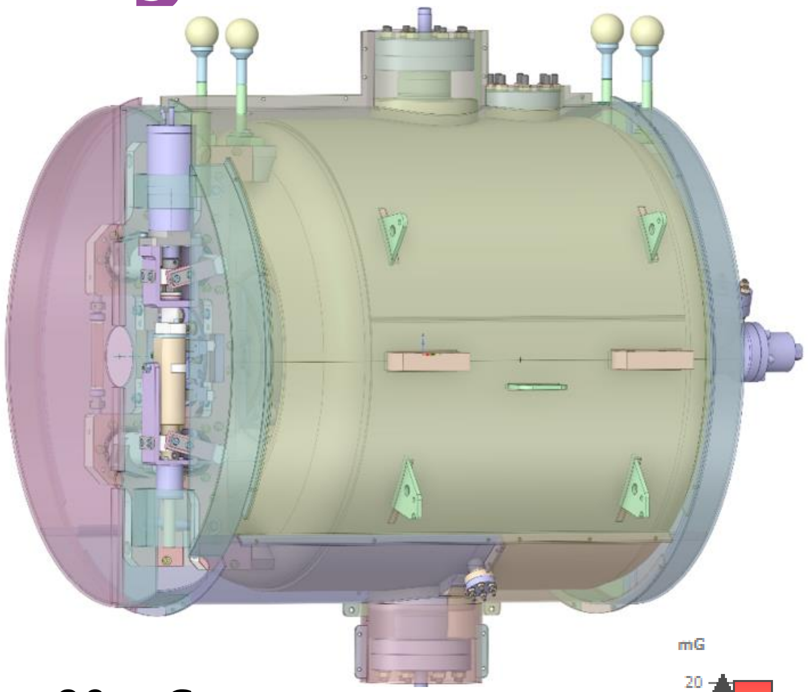


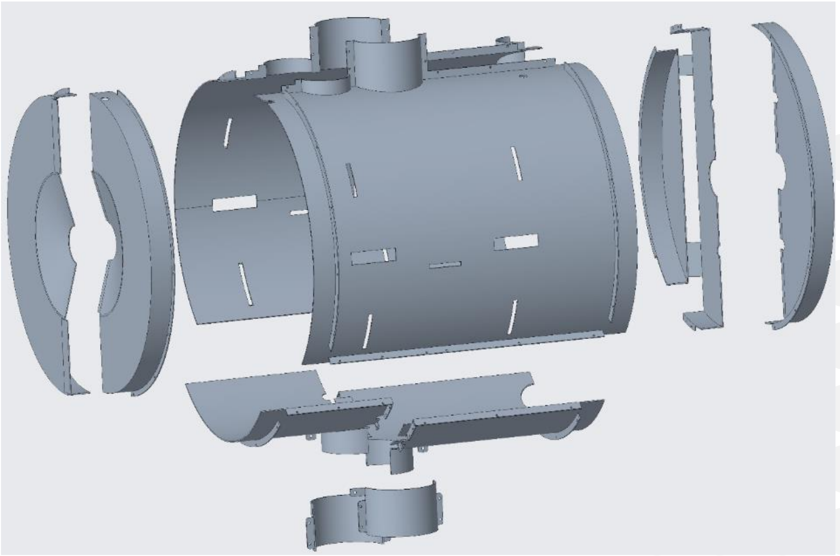
SRF Spoke Cavities

- Pre-series tested at IJCLab,
  - 4 from 6 cavities were re-tested @ FREIA with similar results
  - Typical limitation: Field emission
- Series testing being done at FREIA (Uppsala)

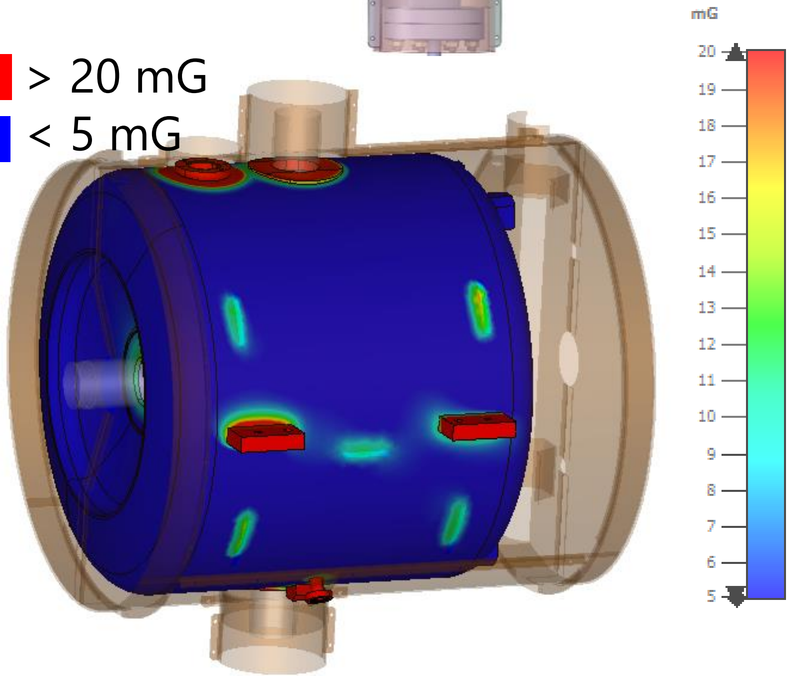


Magnetic shield





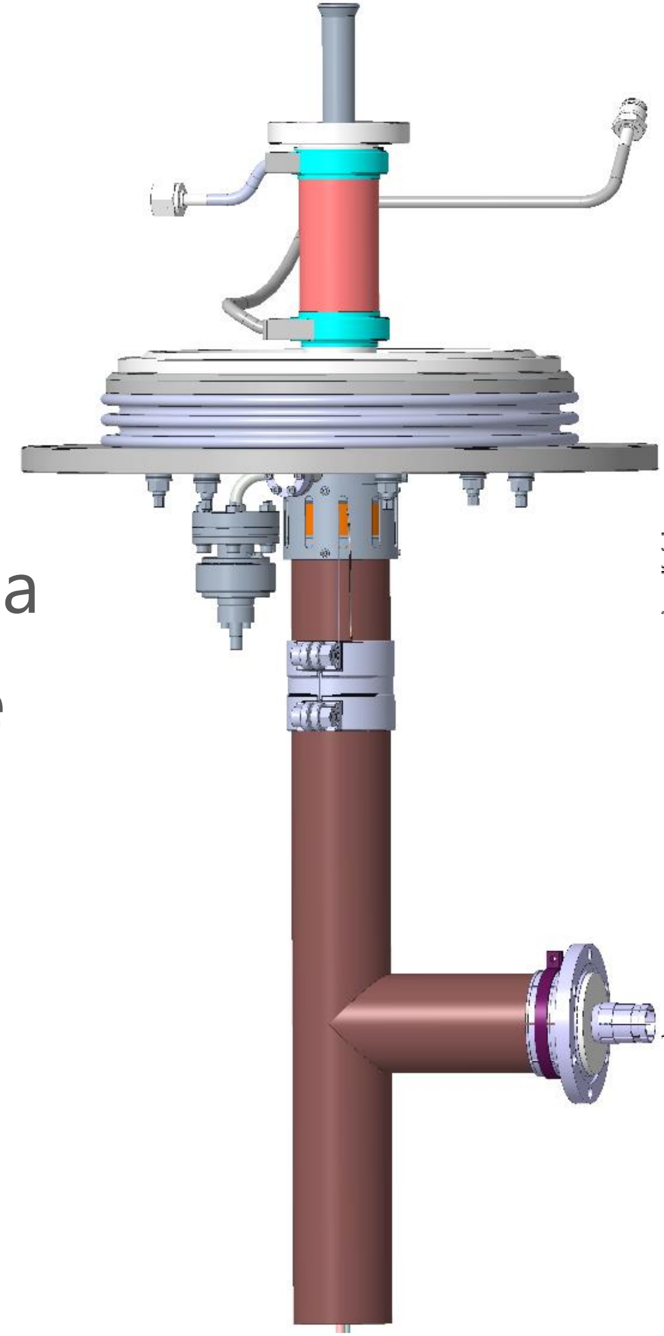
> 20 mG
< 5 mG

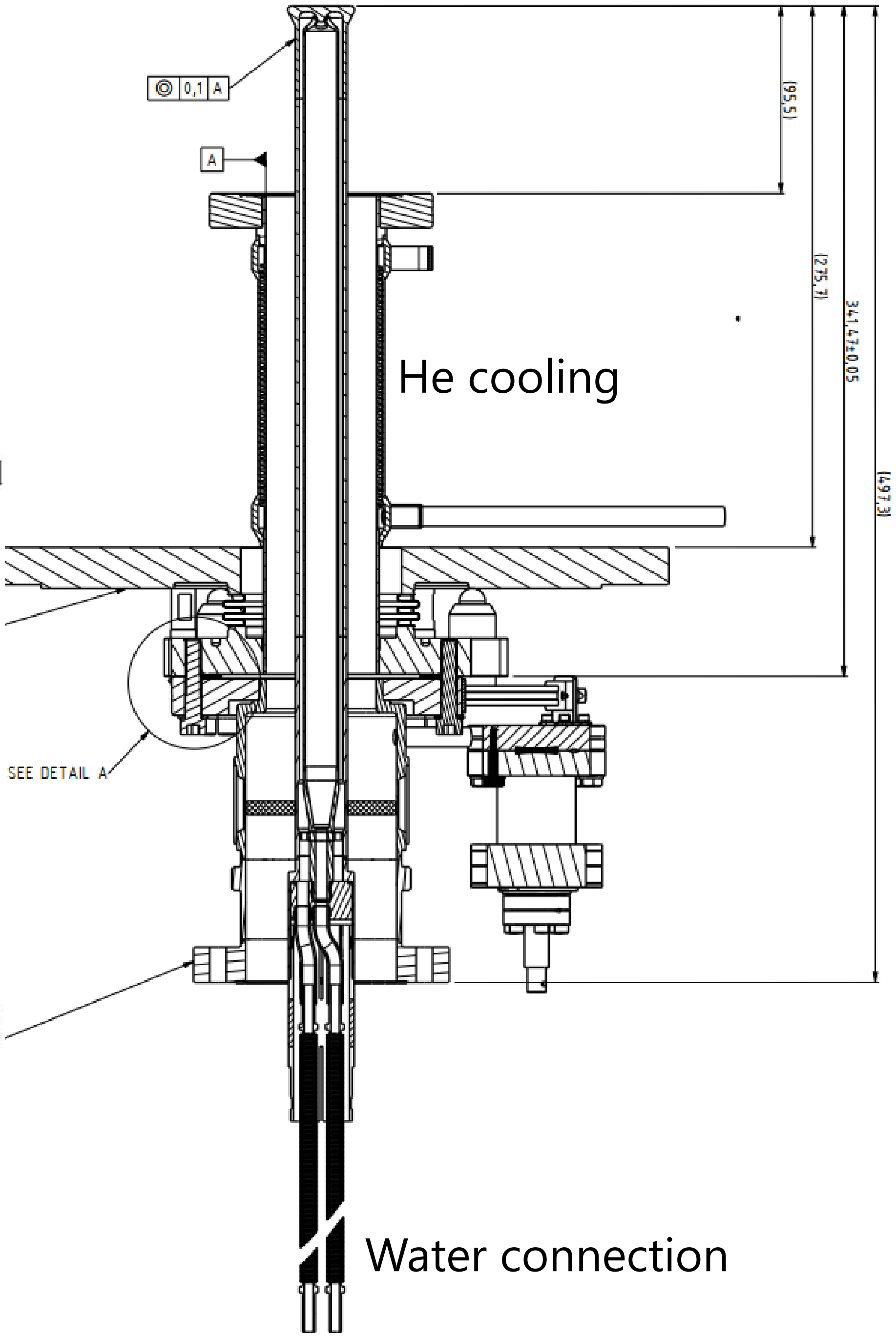


Manufacturing ongoing at Meca Magnetic

RF Coupler

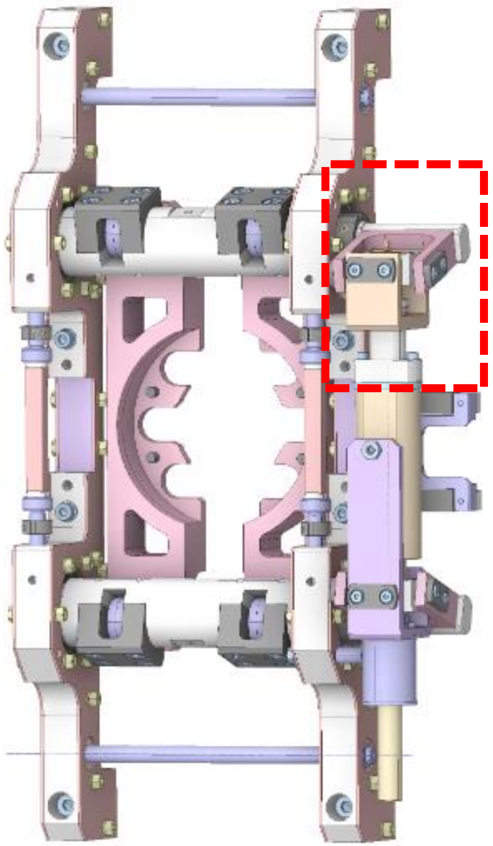
- Water-cooled inner antenna
- SHe-cooled outer coax line
- TiN-coated RF window
- Tender in publishing
- RF-Conditioning at IJCLab





Cavity tuning system

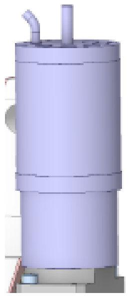
- **Fast & frequent detuning needed**
- Core part designed by IJCLab
- Baseline: warm motor solution but cold motor option as backup
- Conceptual design of the power train and the warm motor assembly are finished.
- Heat loads of power train: <0.5 W@2K
- Upcoming test-stand for warm motor solution at IJCLab



IJCLAb design

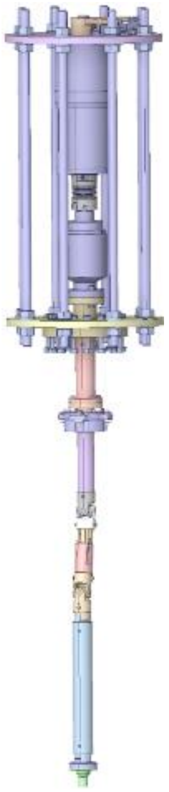
\+

Cold Power Drive

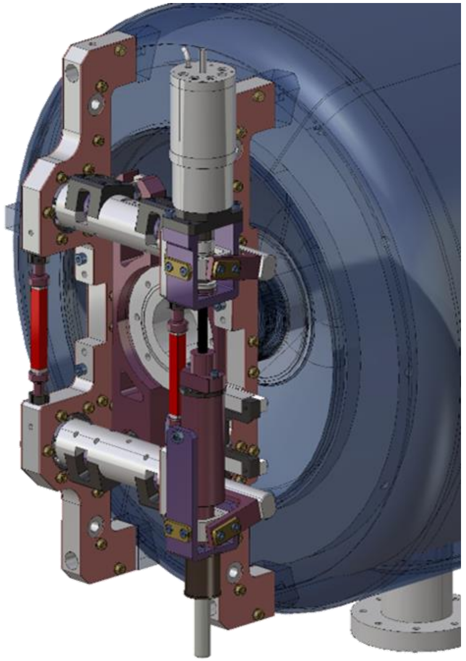


or

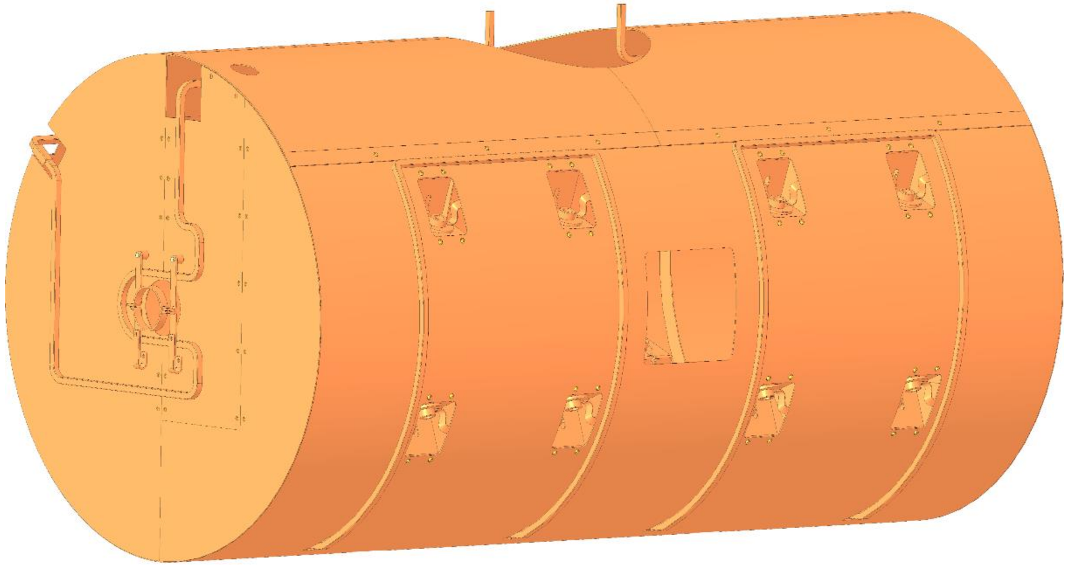
Warm Power Drive

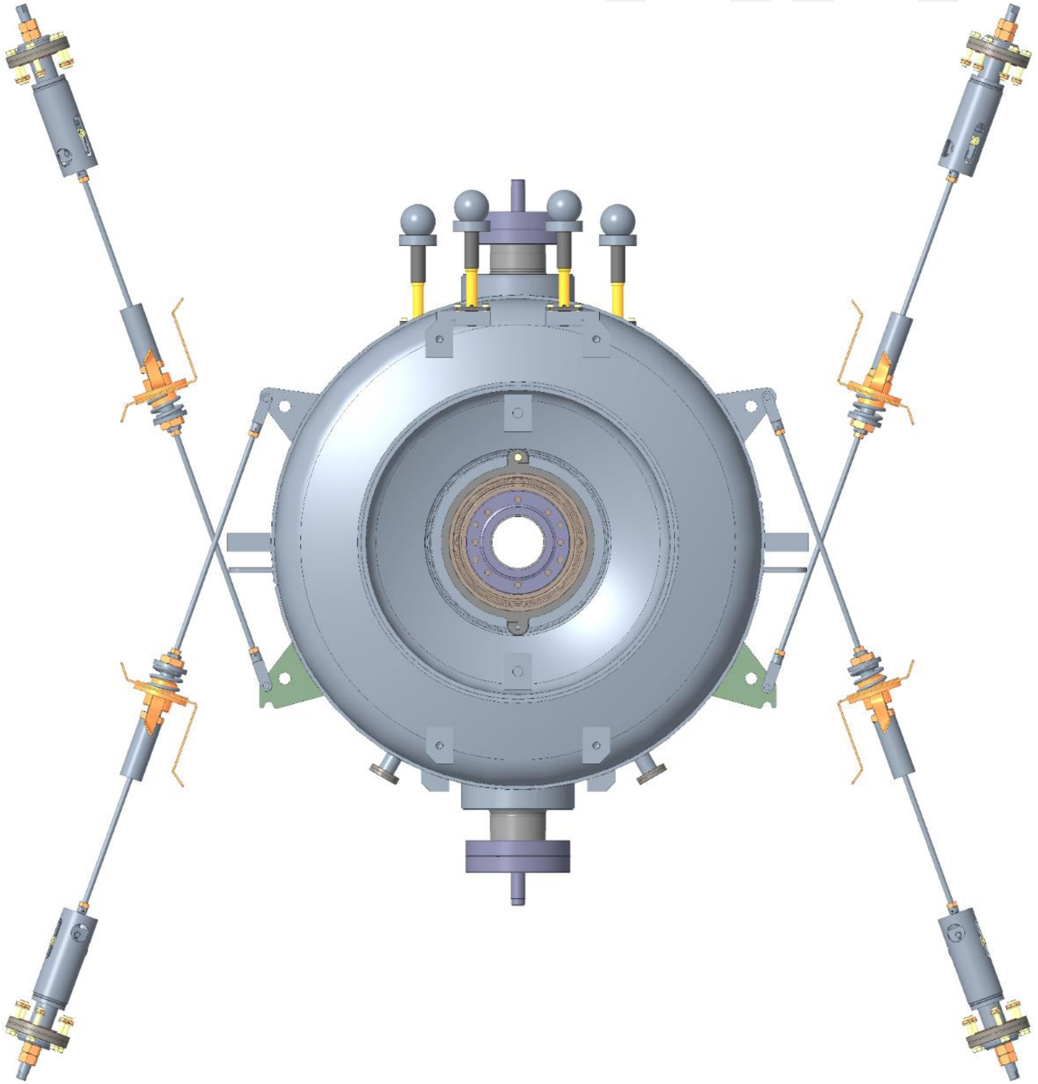


SCK CEN design



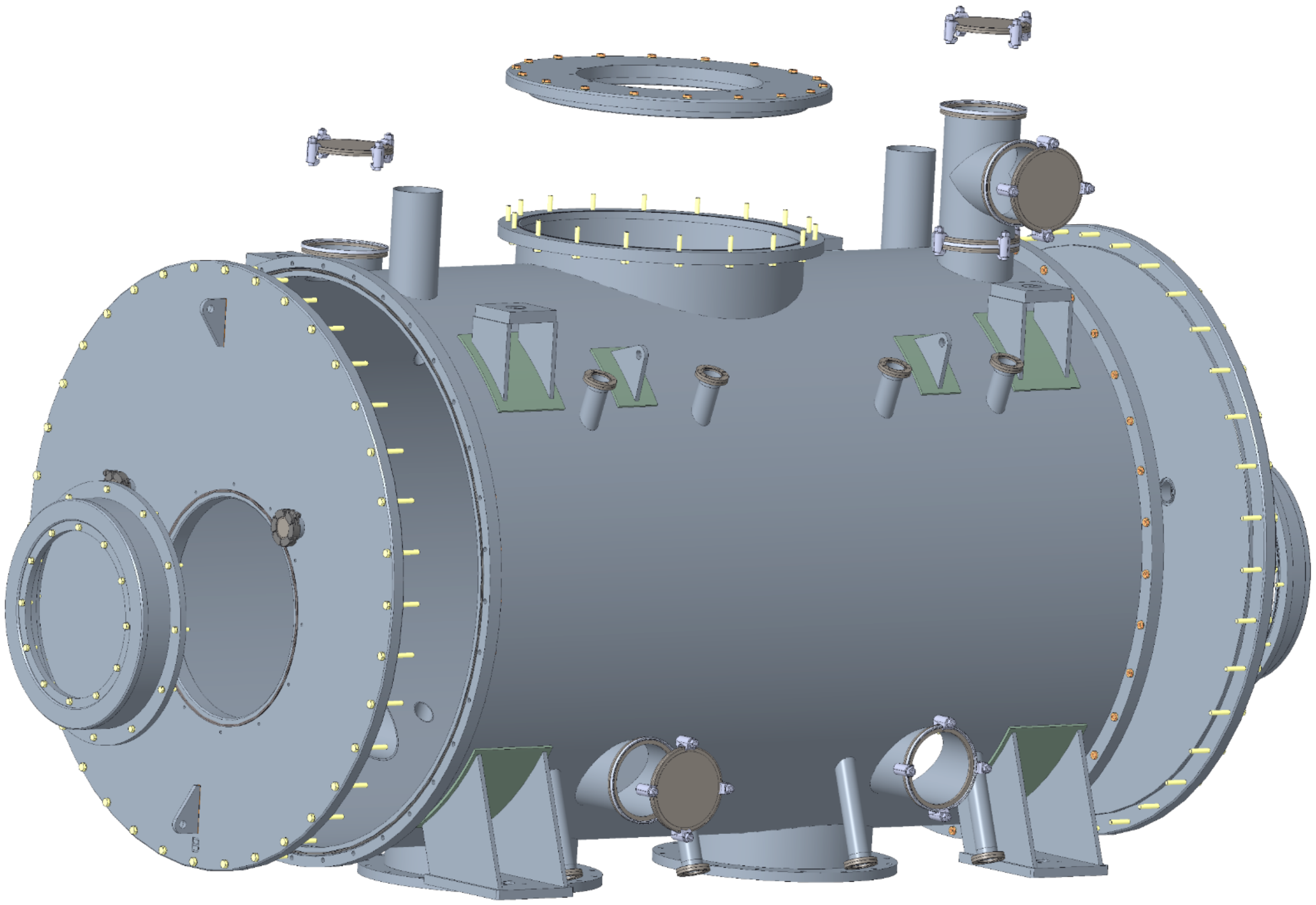
Thermal shield & tie-rods





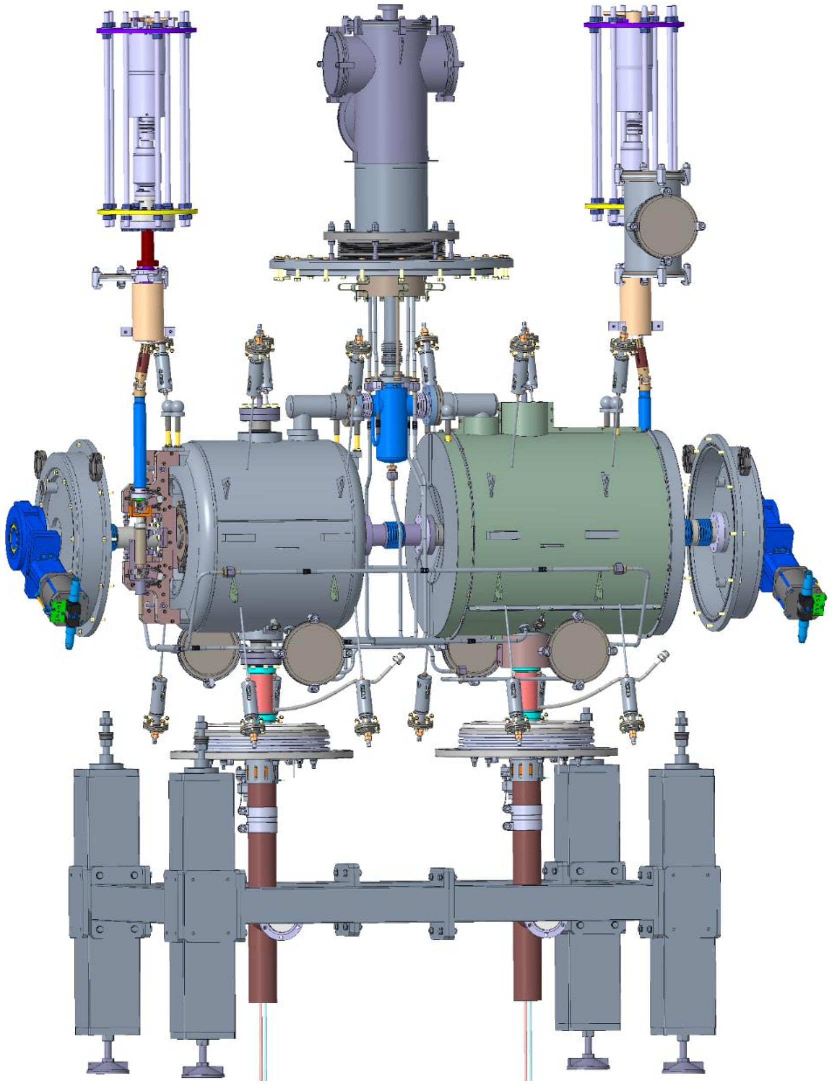
- Made from Aluminum
- Access ports to reach the tie-rods and fiducials

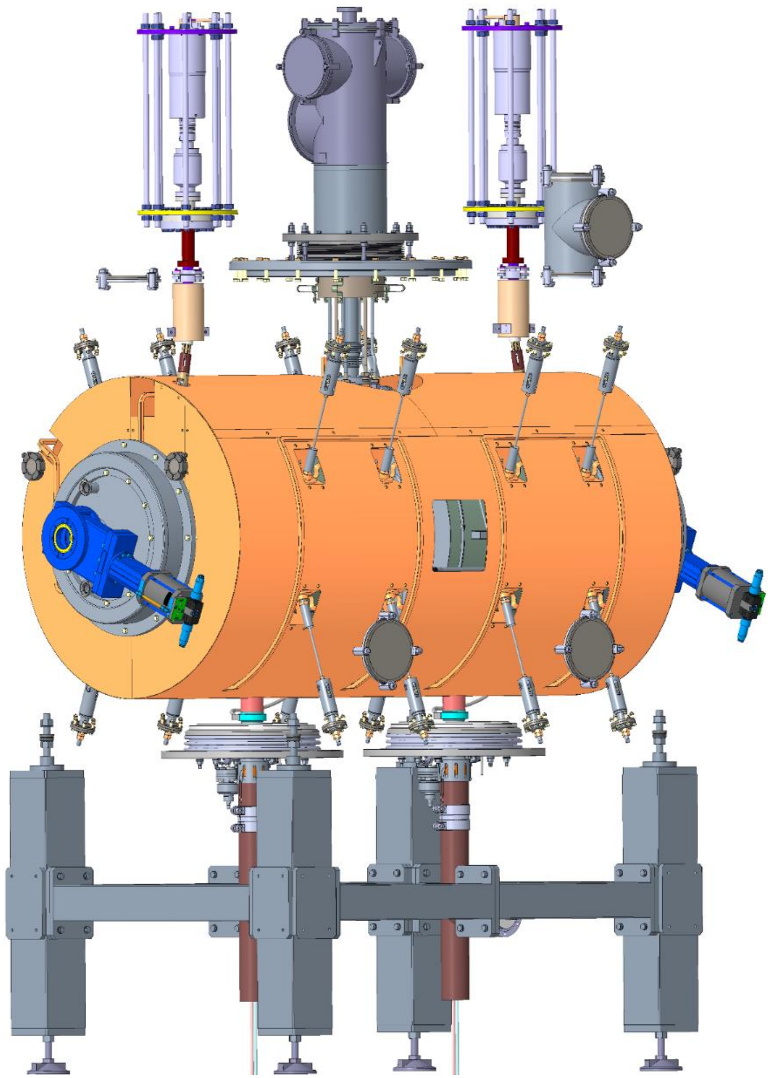
Cryo vessel

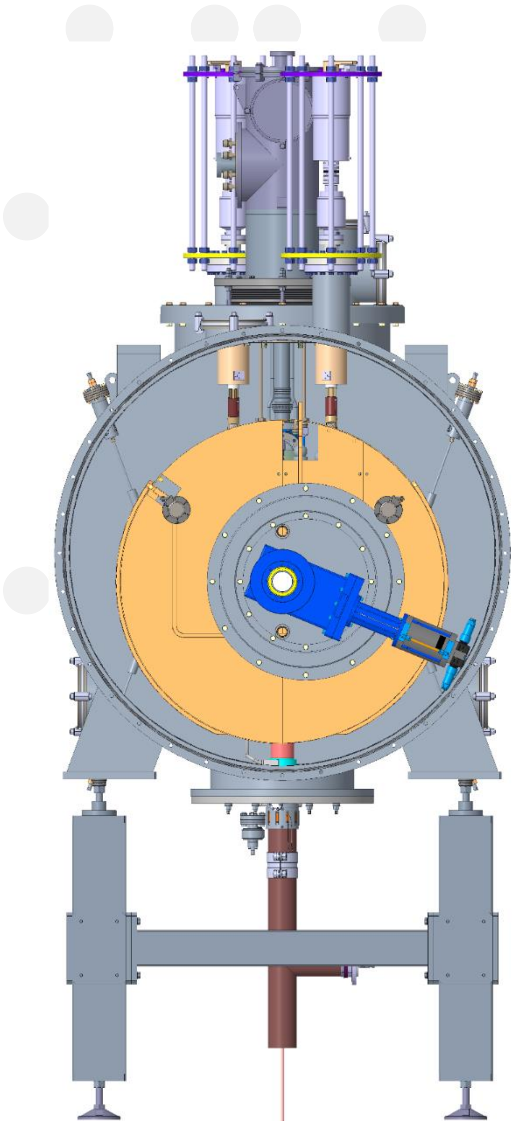


- Standard CF connections are used for the access ports.
- Conceptual buffer tank redesign done

Overview

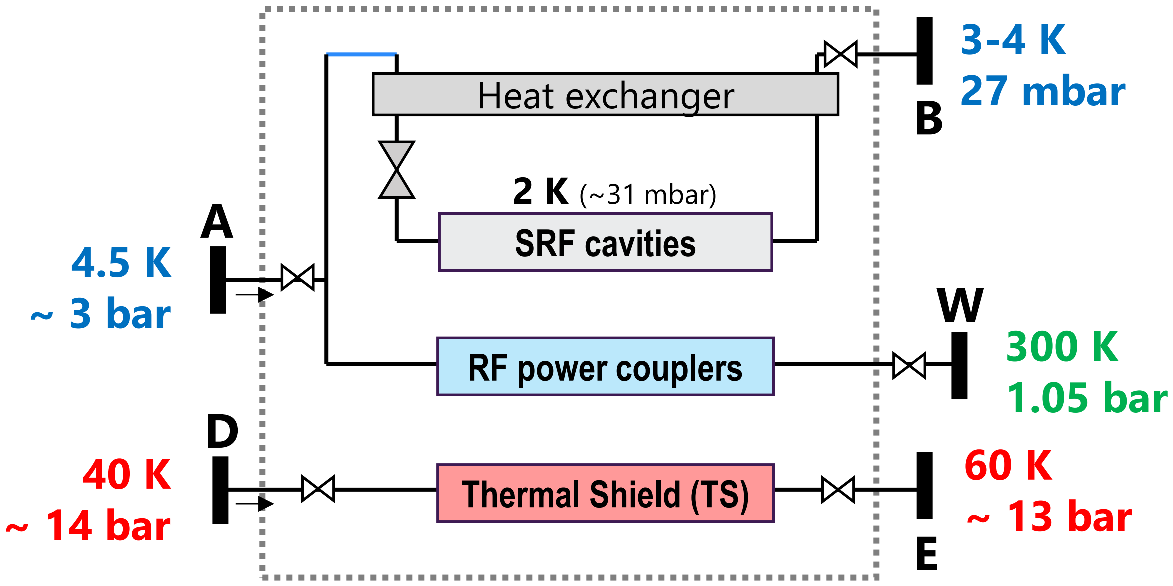






Cooling circuits and heat loads

Simplified cooling circuits of one QCELL as seen by the cryogenic distribution



Required cooling capacity (static | dynamic | total), excluding contingency margins.

Equipment	2 K Circuit [W]	TS Circuit [W]	Coupler Circuit [g/s]
Single QCELL	13.9 | 9.1[a] | 23.0	184 | - | 184	0.040 | 0.012 | 0.052
- QM only	9.3 | 9.1[a] | 18.4	122 | - | 122	0.040 | 0.012 | 0.052
SRF linac			
- Min turndown [b]	334 | - | 334	4423 | - | 4423	0.96 | - | 0.96
- Nominal operation	418 | 187 | 605	5529 | - | 5529	1.20 | 0.36 | 1.56
- Max. operation	418 | 242 | 660	5529 | - | 5529	1.20 | 0.16 | 1.49

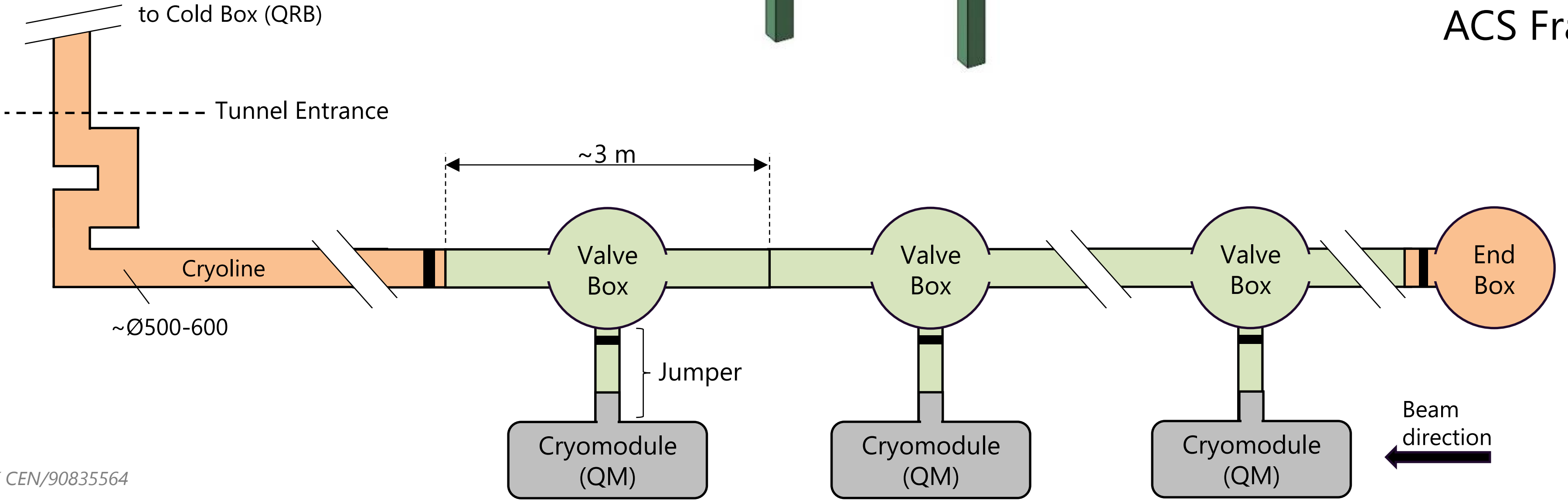
[a] 4.25 W of RF losses per cavity at 7 MV/m. [b] hypothetical staged installation of 24 QCELLs.

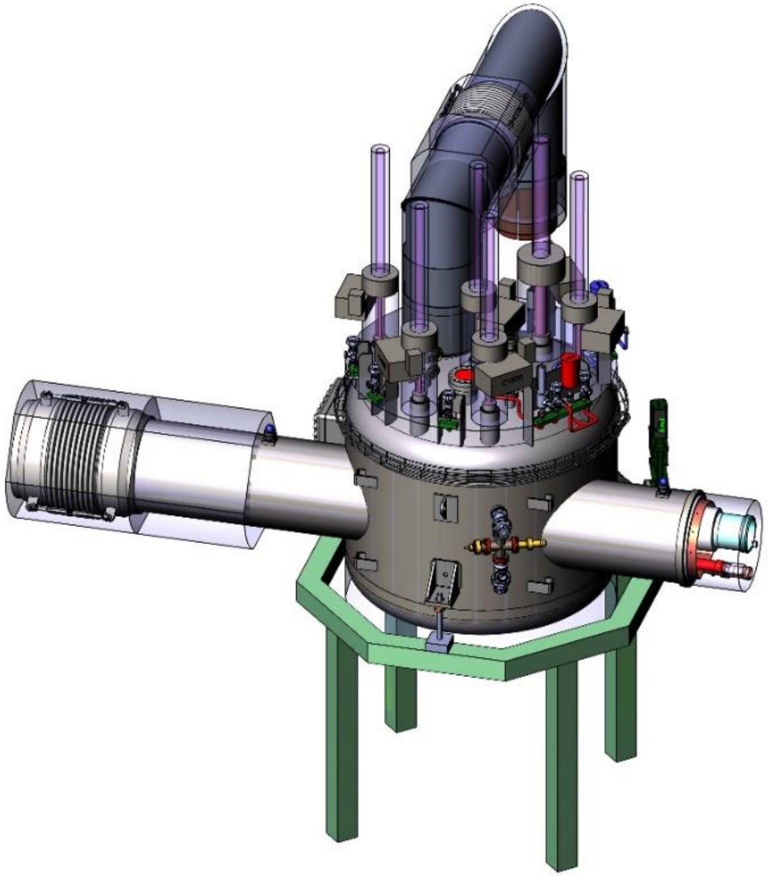
Margins for cryoplant sizing

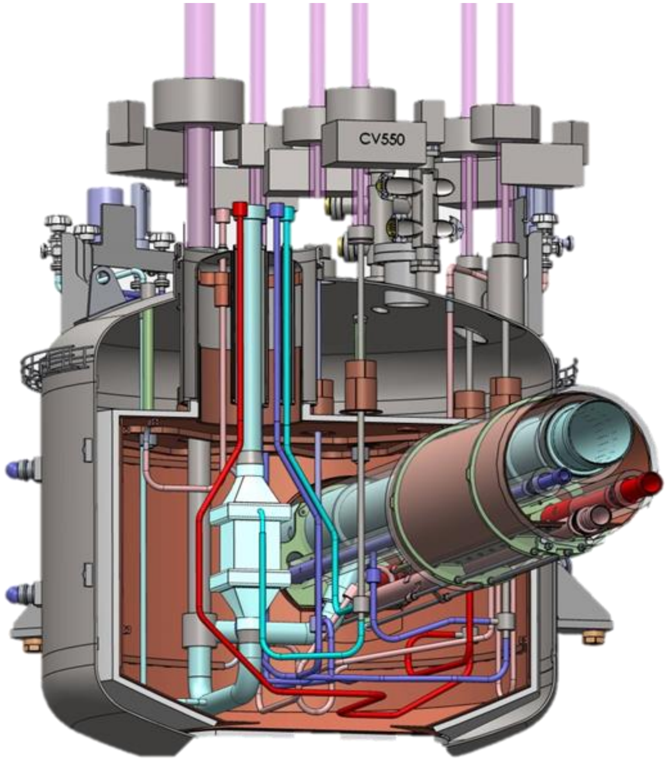
- No margin → Min turndown
- Full margin +50% → Nominal operation
- Limited margin +20% → Max. operation

CRYO Backbone

Reference design by ACS
Design and implementation in final tender preparation





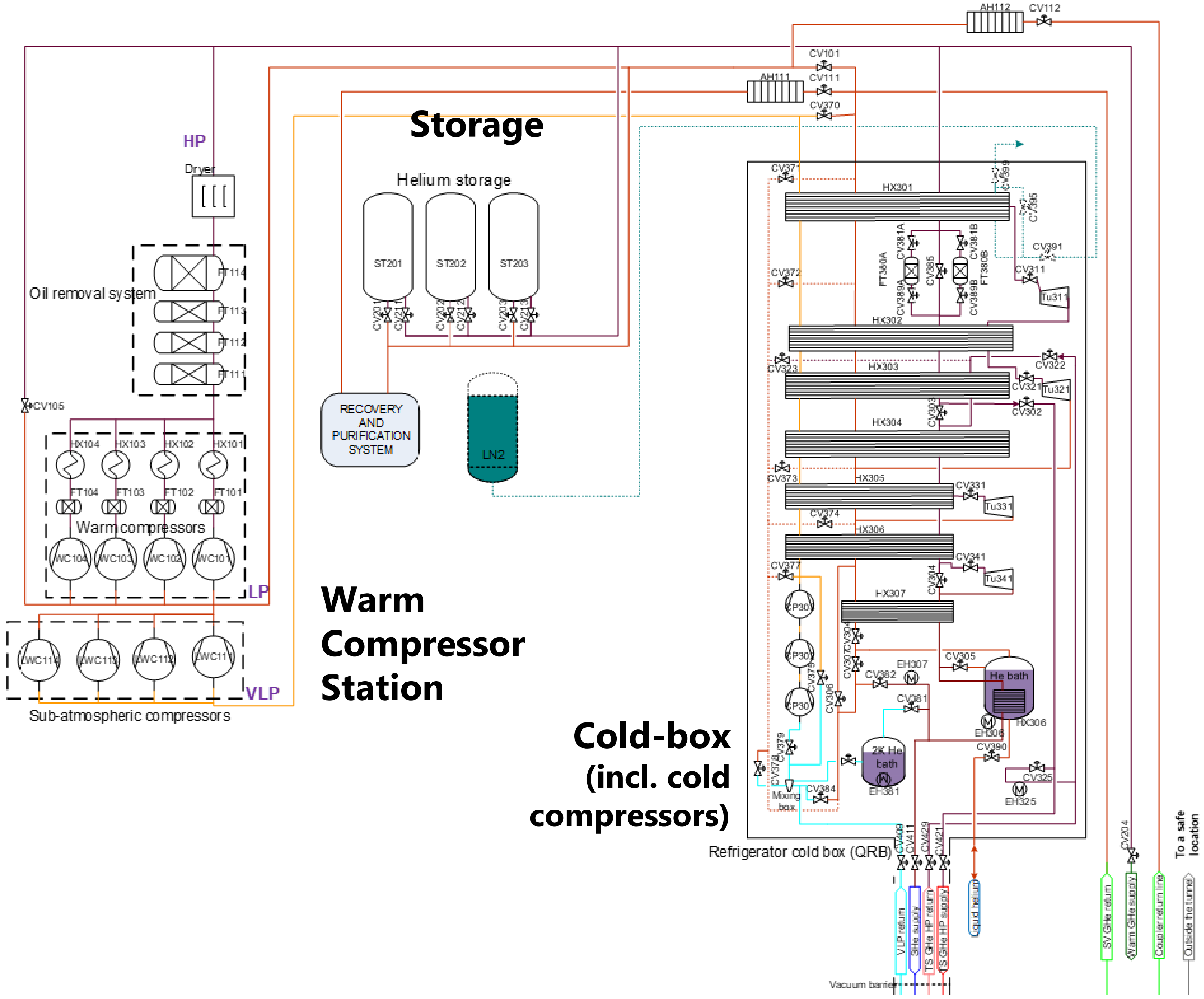


ACS France

Cryoplant

Cryoplant Architecture

- **~ 3.5 kW @4.5 K**, of which
- **~ 900 W @2 K** (70% of total heat loads)
- ~ 700 kg of Helium inventory



Other Components

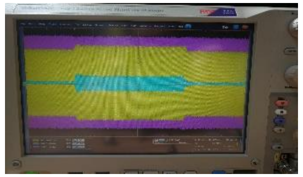
- Solid state amplifiers
  - Being produced by Cyroelectra
  - Drain voltage adaptation for efficiency gain
- MPS:
  - 1W/m
  - Differential beam current measurement & beam loss monitors
- Magnet design & follow up by ACT
- LLRF
  - RF based PRDS (being tendered)
  - Great collaboration with DESY!
    - E.g. aiming for direct sampling with DESY-uTCA card developed for Petra IV
  - CW quench detection/protection …
  - 0.1° phase, 0.1% amplitude

Low-Level RF project: history, strategy, outlook

2021

Prototyping RFSoC technology

Success with beam RFQ + 2 x QWR



Decision: LLRF will be in-house development

2022

Hiring 4 new engineers + training

Start collaboration with DESY MSK

2023

Procurement strategy
Requirements analysis
Technology survey (**µTCA**)

2024

Conceptual Design:

- Cavity Field Controller
- Cavity Resonance Controller
- Local Protection System
- Phase Reference Distribution

2025

DESY RFSoC AMC prototype ready

LLRF ready for NCRF cavity test-stand based on same RFSoC chip as final design

2026

In-house RTM prototype ready

LLRF ready for SRF cavity test-stand based on same RFSoC chip as final design

UPPSALA UNIVERSITET

Integration LLRF for **NCRF** in final hardware: DESY AMC + in-house RTM

2027

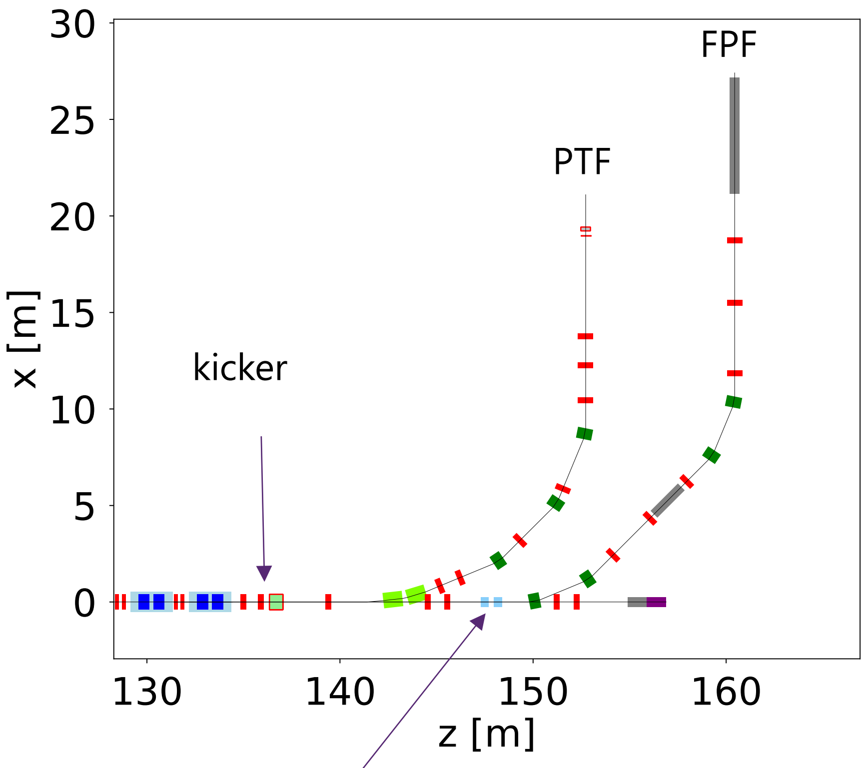
Installation NCRF Commissioning

Integration LLRF for **SRF** in final hardware: DESY AMC + in-house RTM

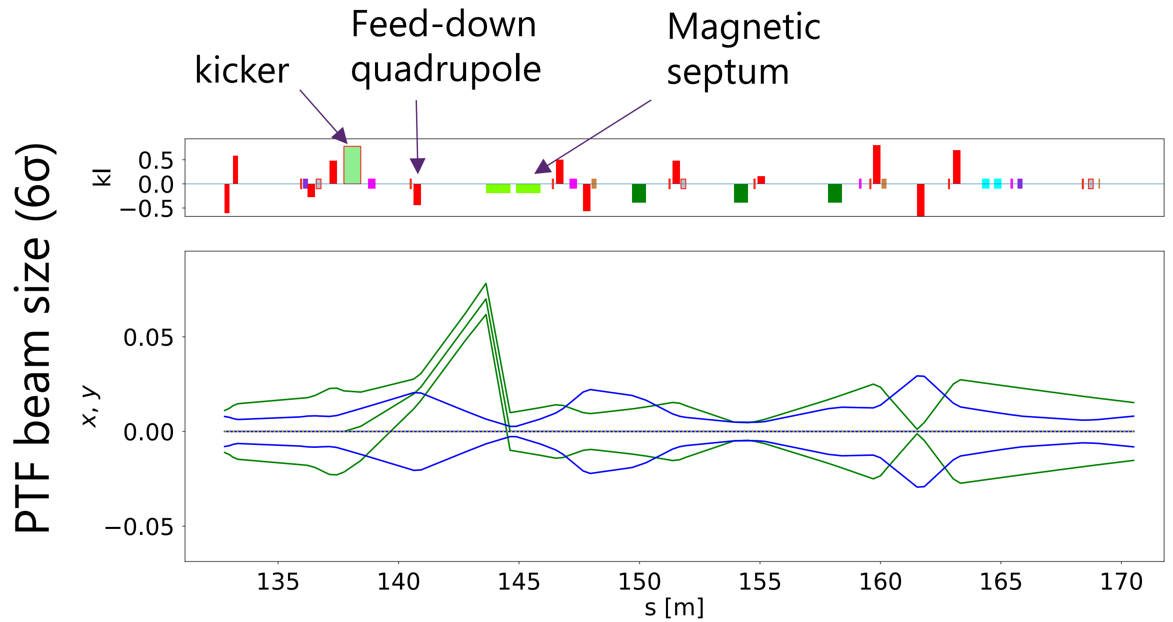
2028

Installation SRF

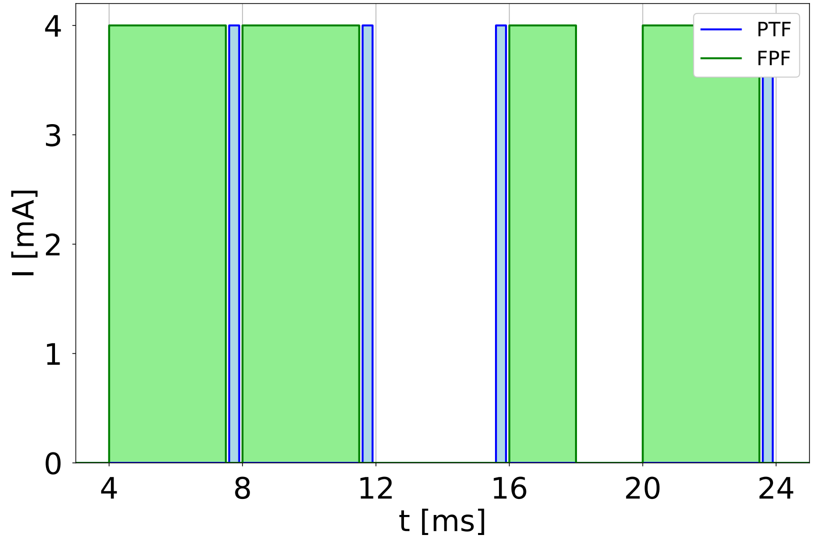
100 MeV “HEBT”



Space for SC-rebunching cryo-module for matching to future medium beta linac

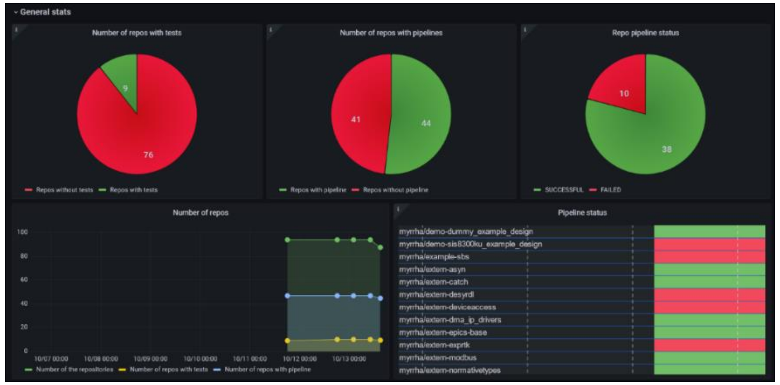


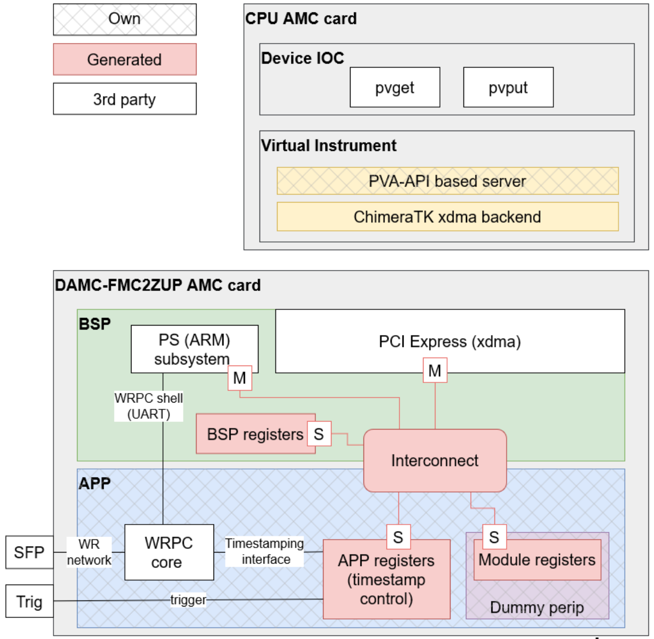
Pulse pattern
(RF = CW)



Control system

- **Agile** based lifecycle including **DevOps** and **Test Driven Development (TDD)**
- based on **EPICS**, **µTCA4**, **White Rabbit** and standard industrial solutions
- **In-house team of 6 persons** to coordinate and gather input
- Solution delivery mainly by ***Framatome Hungary*** and ***EvoPro Innovation***

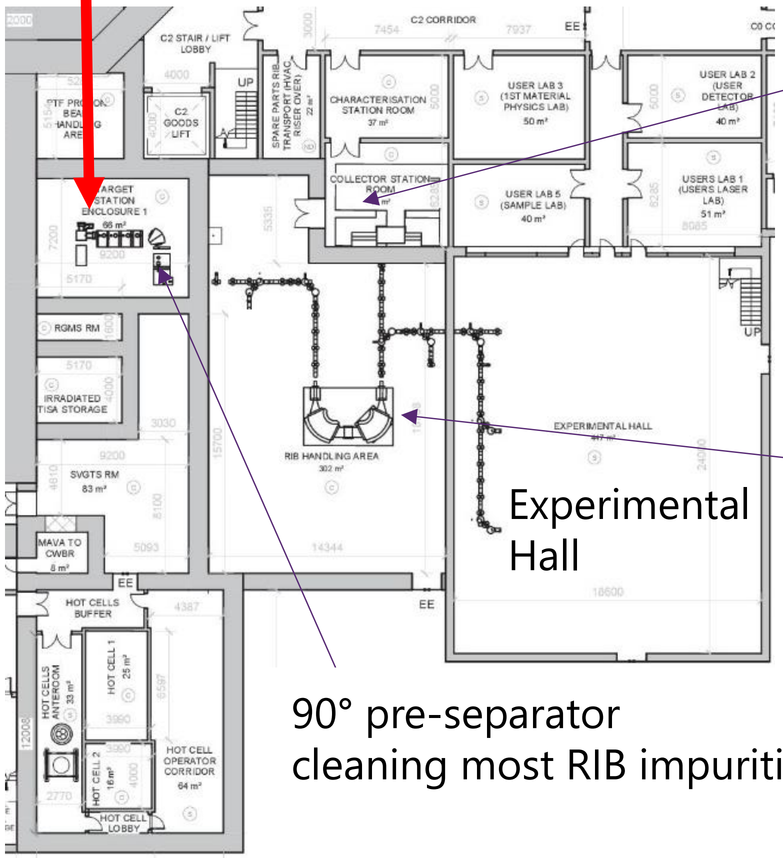




PTF: ISOL

- TRIUMF ARIEL concept at the basis of the facility design TRIUMF
- 4mA, ≤ 250Hz, ≤ 0.5ms on non-actinide or ≤ 0.2ms on actinide targets
- RIB mass resolving power: initial ≈1500, upgradable to 10 000

100MeV protons



Isotopes collector station

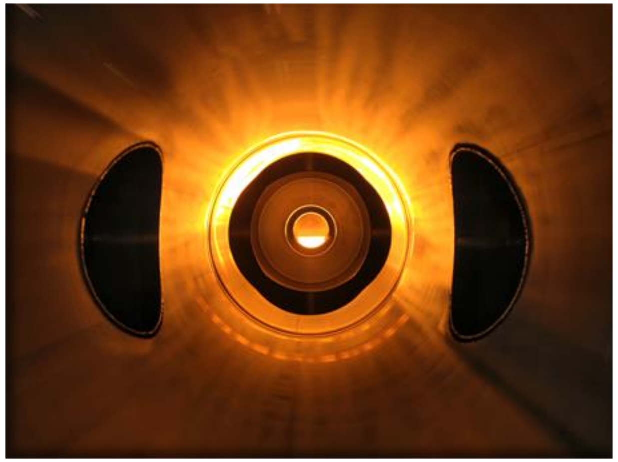
RIB-handling and purification system

Experimental Hall

90° pre-separator cleaning most RIB impurities

Test stand available

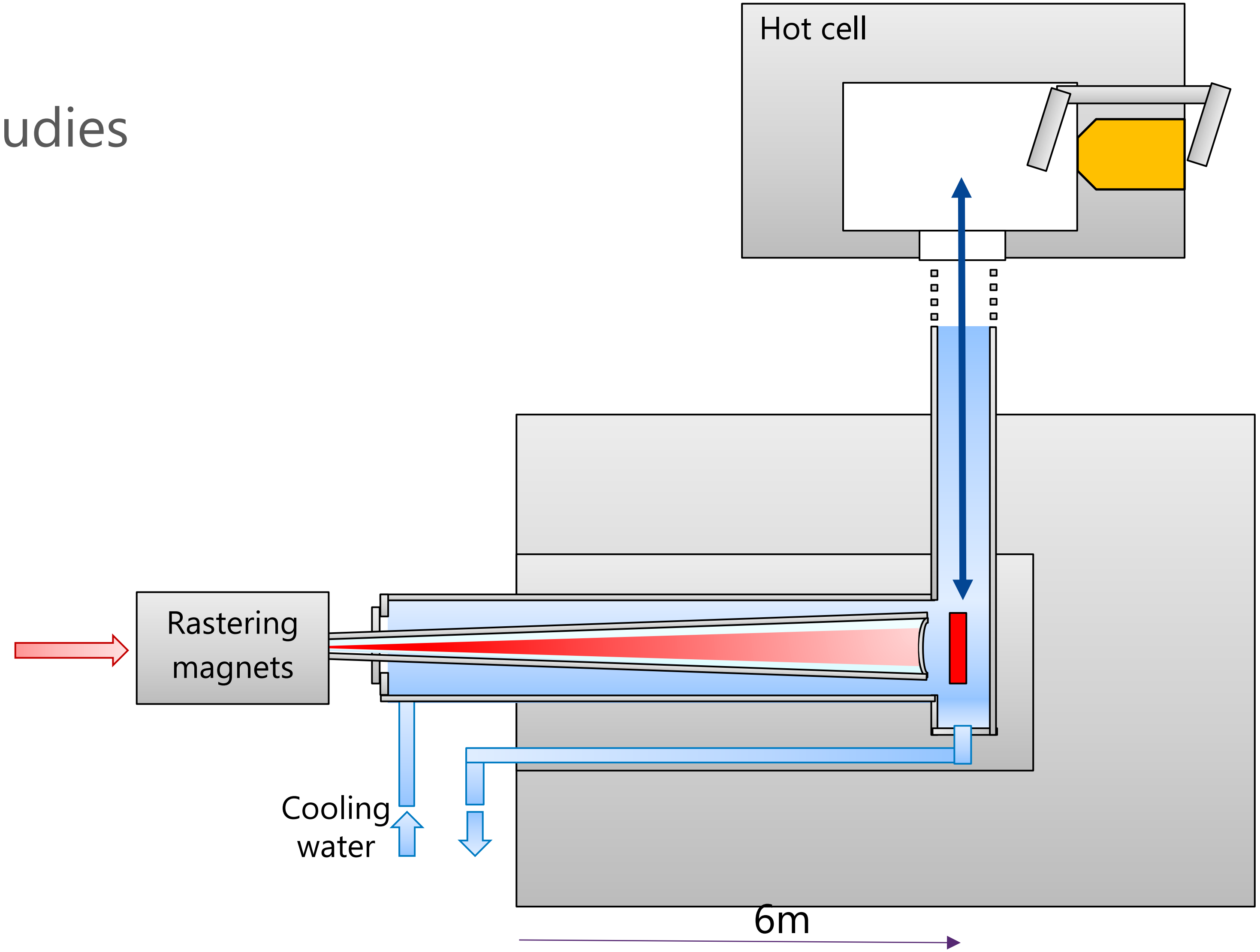
Target heated up to 2000K



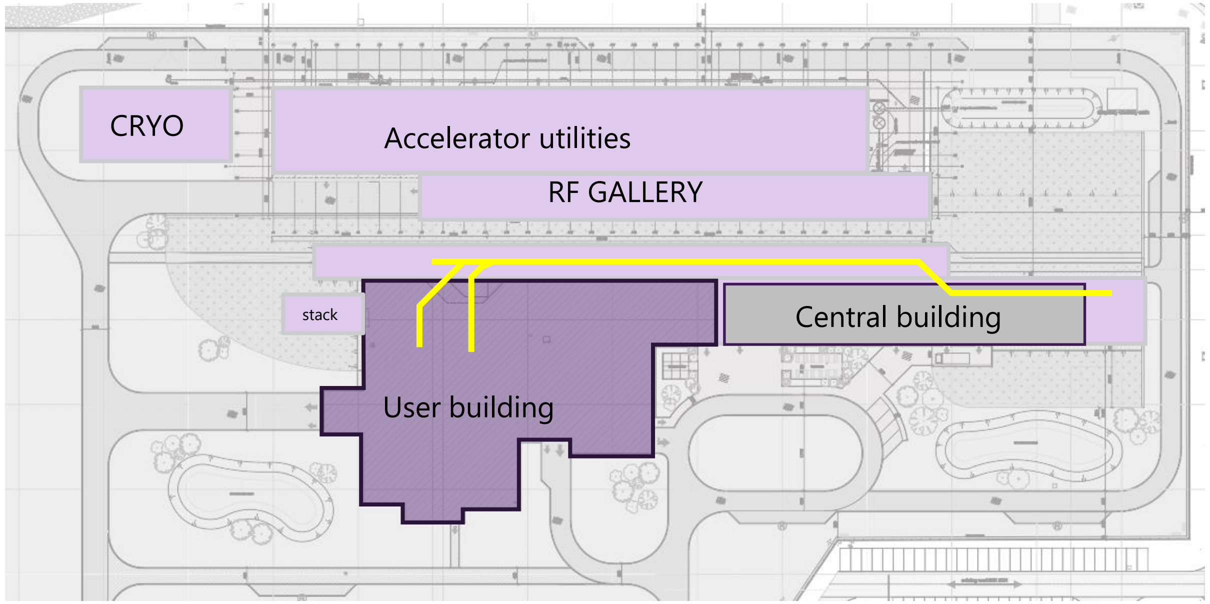
Full Power Facility (FPF)

- Inspired by IPF@LANSCE
- Beam dump for reliability studies
- Fusion material research:
  - Direct proton irradiation
  - Via spallation neutrons

Beam window test stand



Building & infrastructure



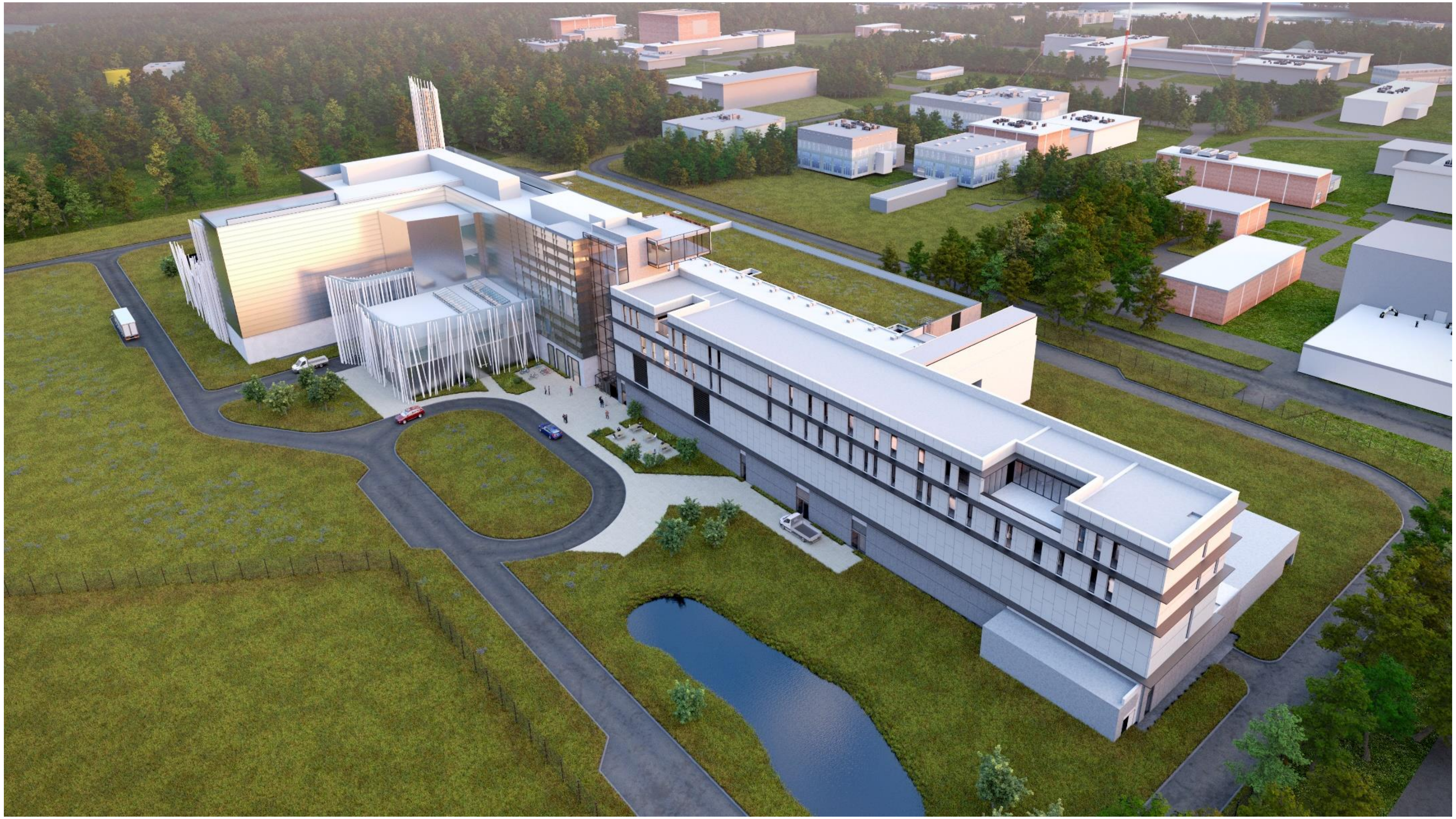
- Footprint:
  - Accelerator related: 8 000 m²
  - User building: 3 600 m²
- Electrical: 9.8 MVA

- **Approach:**
  - One Design Engineer from conceptual design till commissioning
  - Buildings, systems and specialized systems contractor

Construction progress

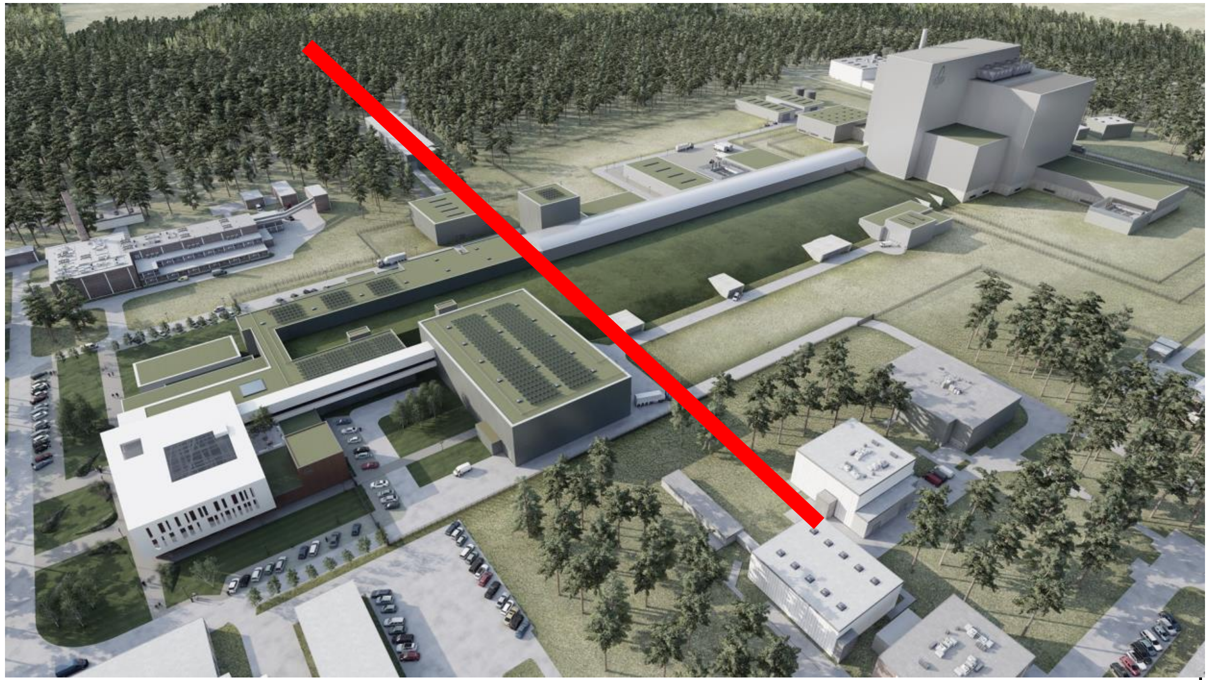
- Official groundbreaking Q2'24
- Construction start Q4'24

Facility layout



Summary

- MYRRHA Phase 1 is funded & international not-for-profit organization established since 2022 as legal entity enabling interested parties (countries, organizations, companies) to join MYRRHA
- Design consolidation of accelerator optics & components finalized
- First series components in production
- Ground breaking in 2024
- Heavily relying on collaborations & industry



Copyright © SCK CEN

All property rights and copyright are reserved.

This presentation contains data, information and formats for dedicated use only and may not be communicated, copied, reproduced, distributed or cited without the explicit written permission of SCK CEN.
If this explicit written permission has been obtained, please reference the author, followed by ‘by courtesy of SCK CEN’.

Any infringement to this rule is illegal and entitles to claim damages from the infringer, without prejudice to any other right in case of granting a patent or registration in the field of intellectual property.

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

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

Registered Office:
Avenue Herrmann-Debrouxlaan 40 - 1160 BRUSSELS - Belgium

Research Centres:
Boeretang 200 - 2400 MOL - Belgium
Chemin du Cyclotron 6 - 1348 Ottignies-Louvain-la-Neuve - Belgium