



The MYRRHA Project

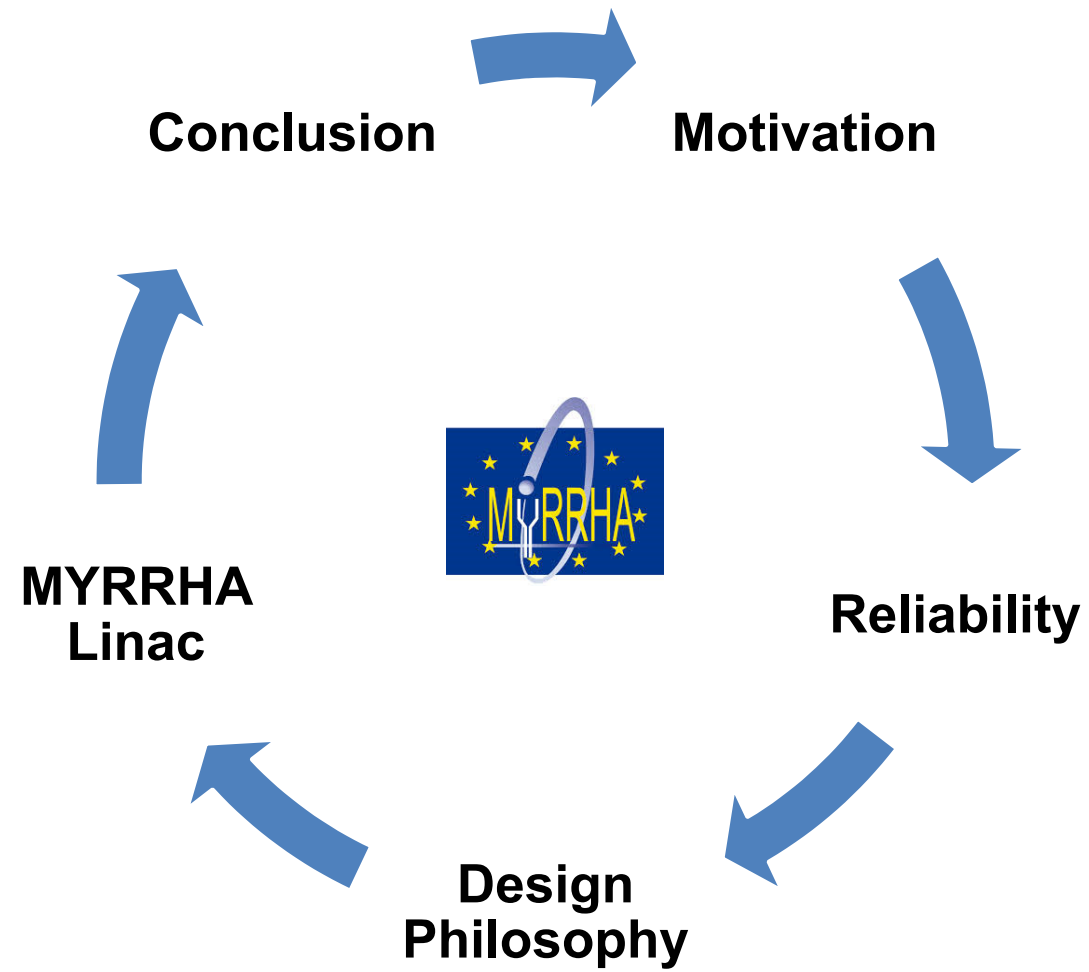
Challenges for a Reliable High Power Proton Linac

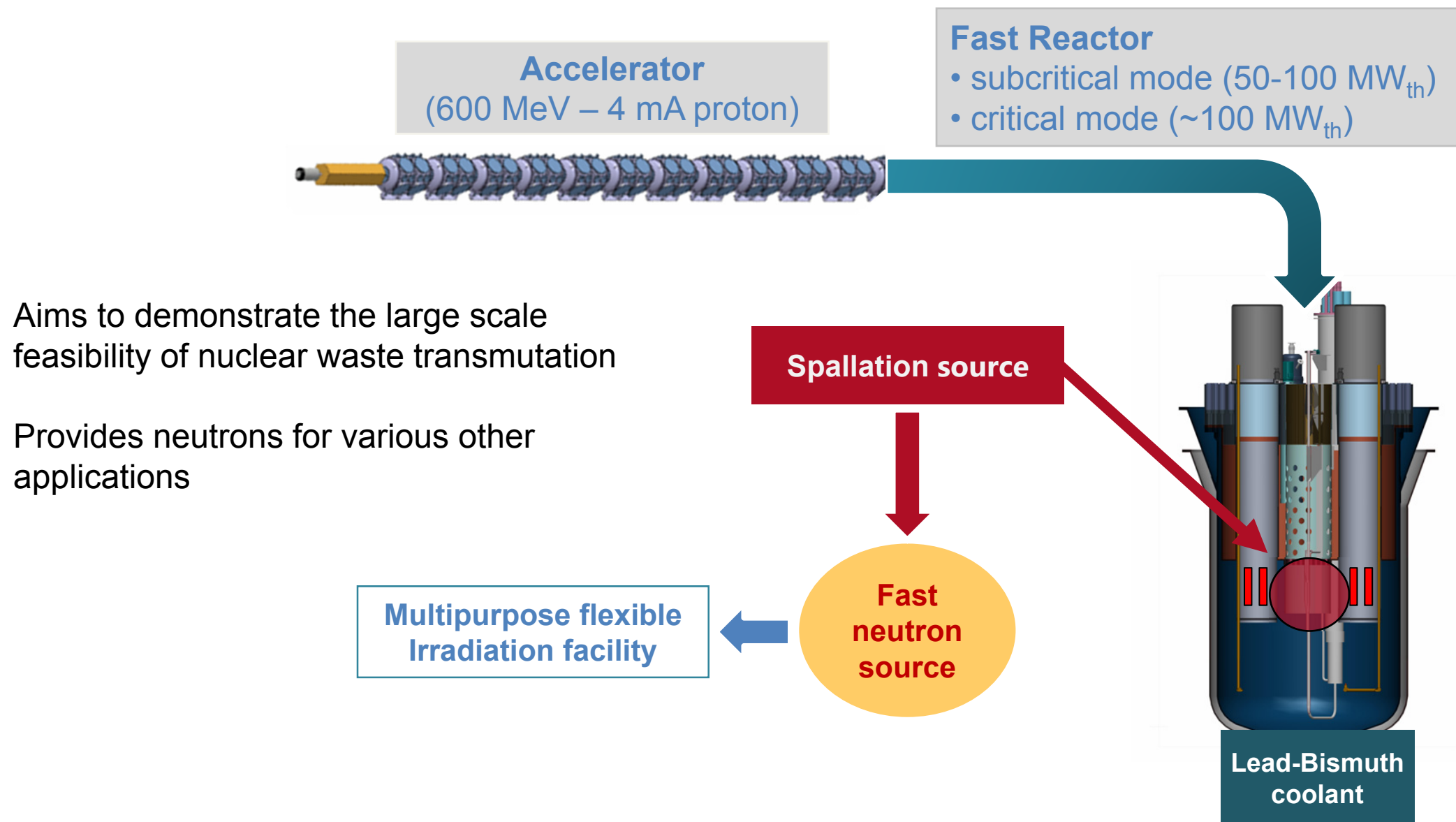
Holger Podlech

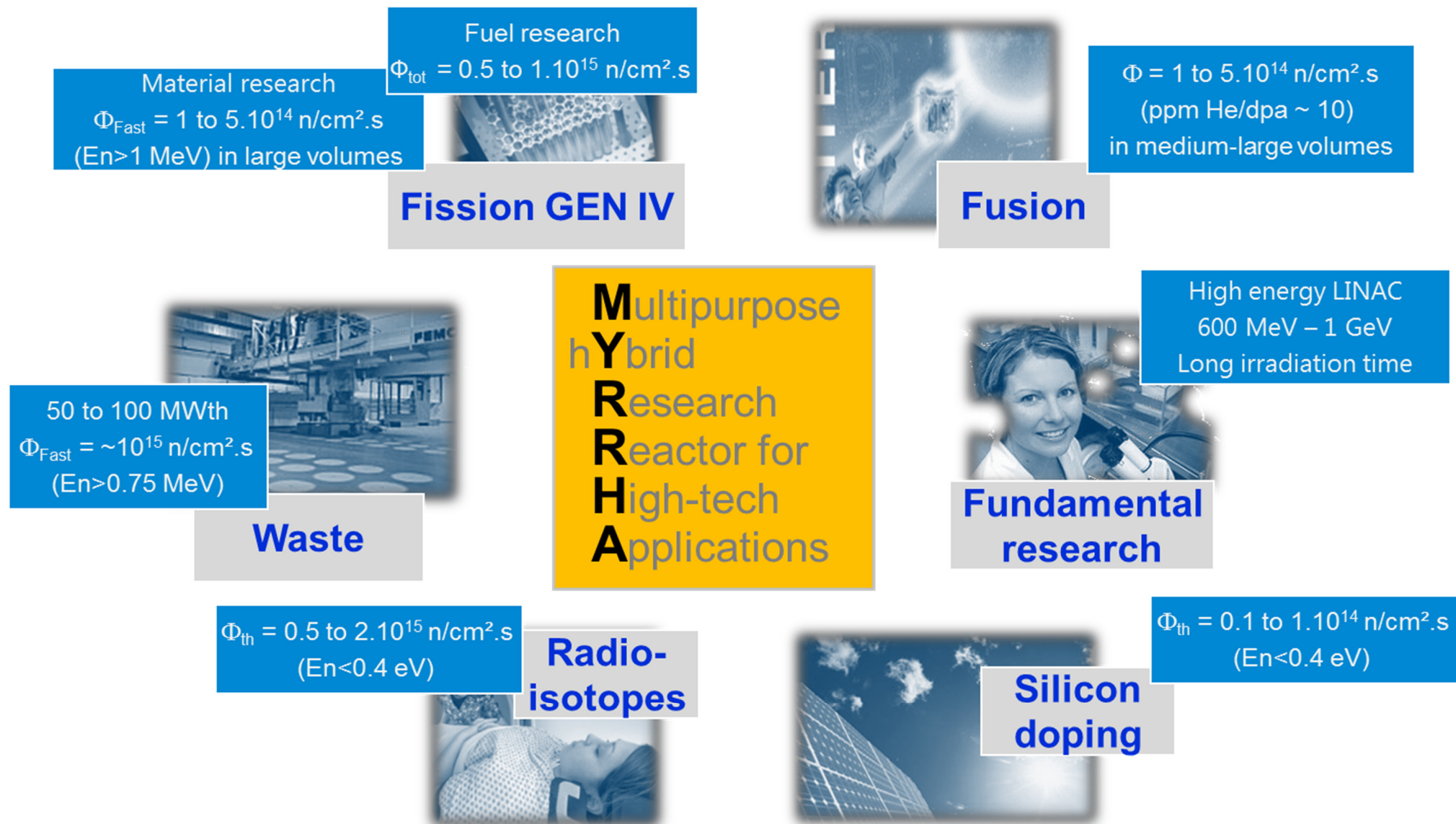
on behalf of the MYRRHA Collaboration

IAP / Goethe University Frankfurt, Germany

NAPAC 2019
Lansing, MI, USA
September 5th







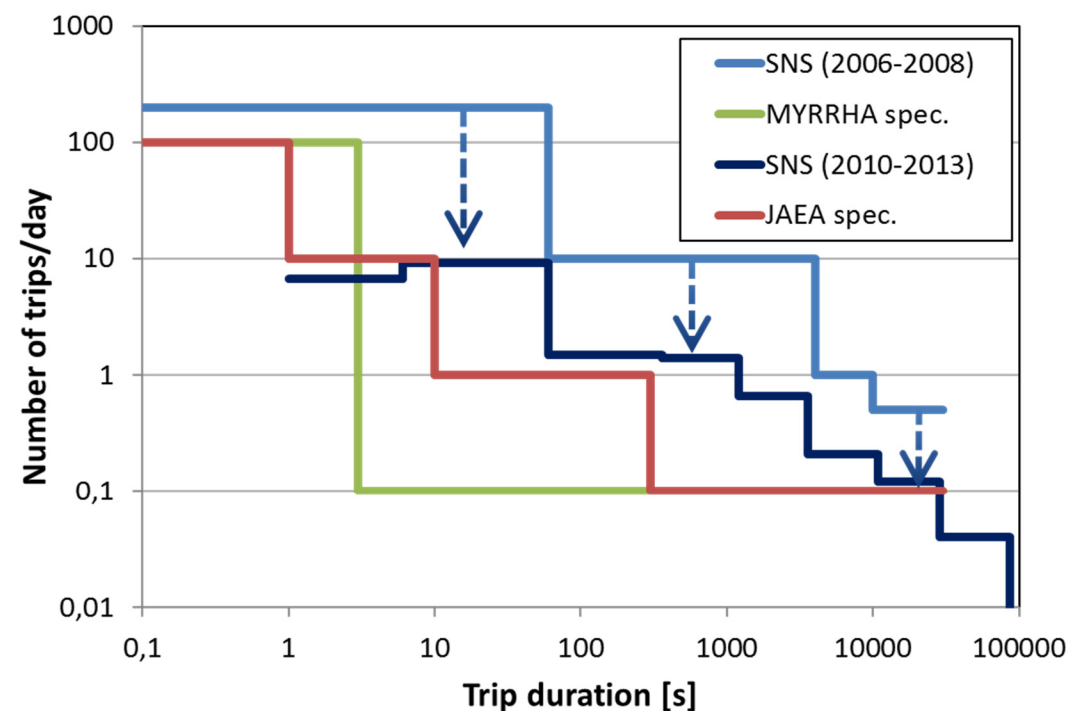
Proton energy	600 MeV
Beam current	0.1 to 4.0 mA
Beam power	2.4 MW
Beam duty cycle	100%
Beam power stability	$< \pm 2\%$ on a time scale of 100ms
Beam footprint on reactor window	Circular $\varnothing 85\text{mm}$
Beam footprint stability	$< \pm 10\%$ on a time scale of 1s
# of allowed beam trips on reactor longer than 3 sec	10 maximum per 3-month operation period
# 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

→ **Extreme reliability level**

Beam trips longer than 3 sec must be very rare:

- To minimize thermal stress & fatigue on reactor structures & fuel assemblies
- To ensure an 80% availability: determined by the foreseen reactor start-up procedures

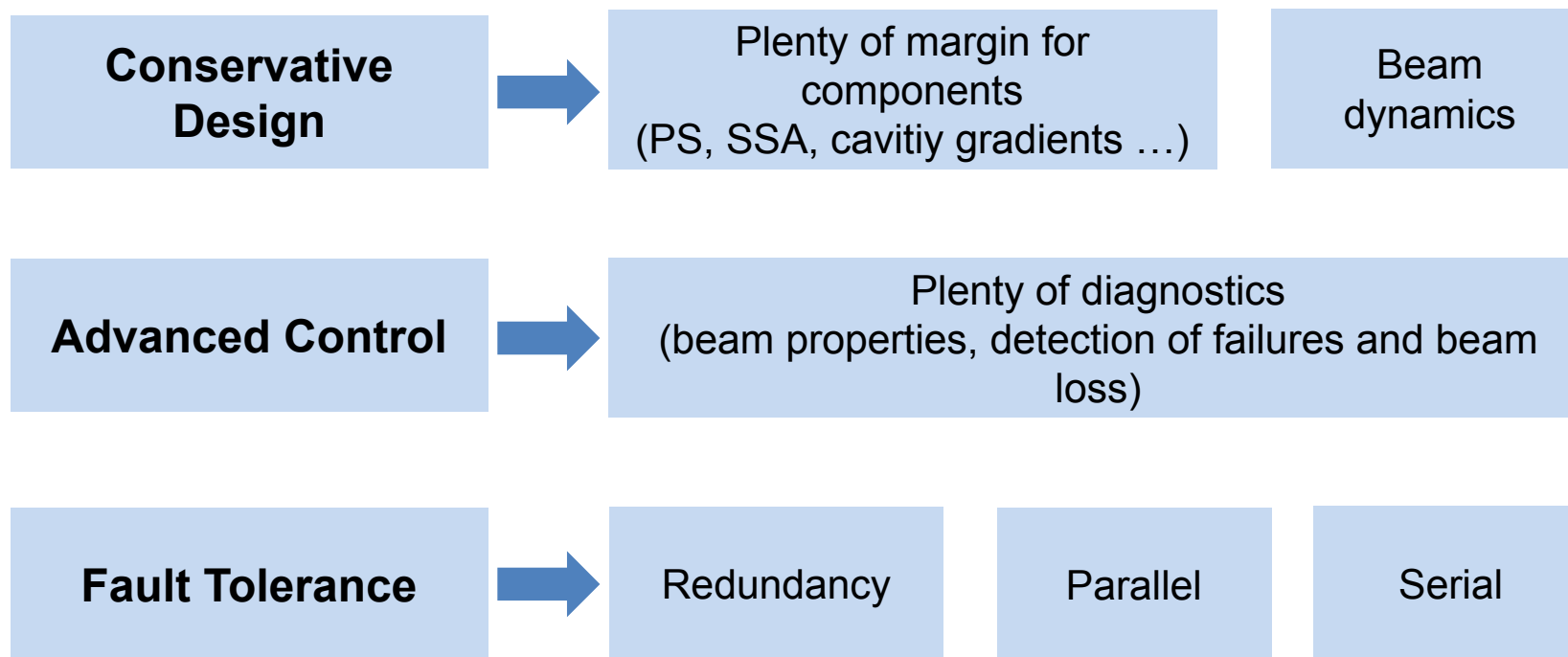
The overall availability (Linac+Reactor) is given by the reliability of the accelerator not by its availability



Conservative design & redundancy

Goal: High Reliability

Measures to reach reliability goal:

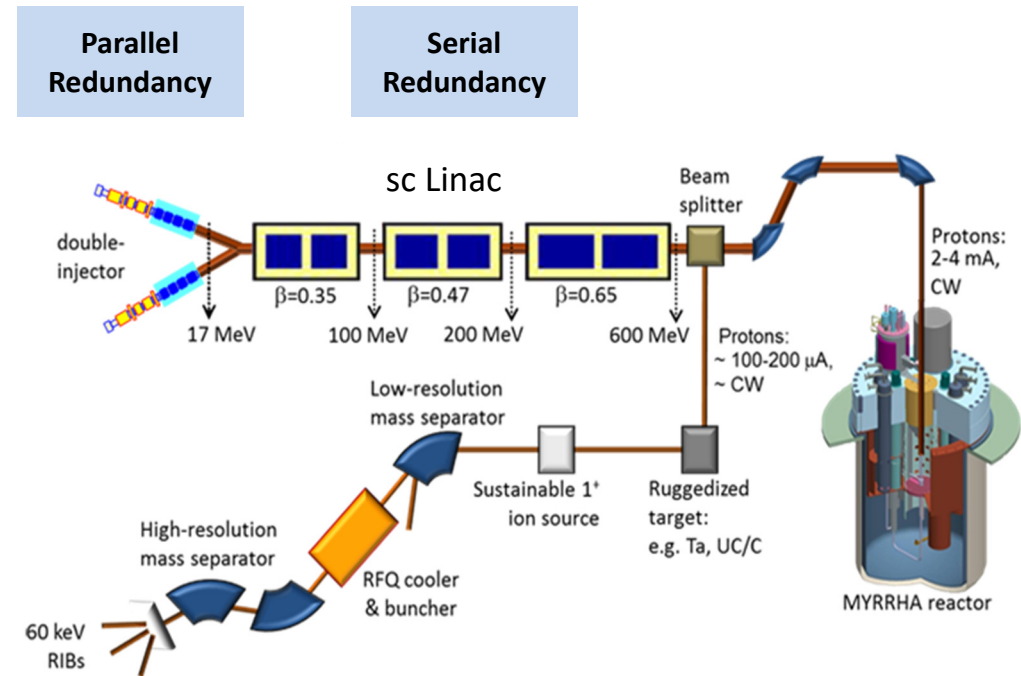


Parallel redundancy: one or more independent systems can provide the requested functionality.

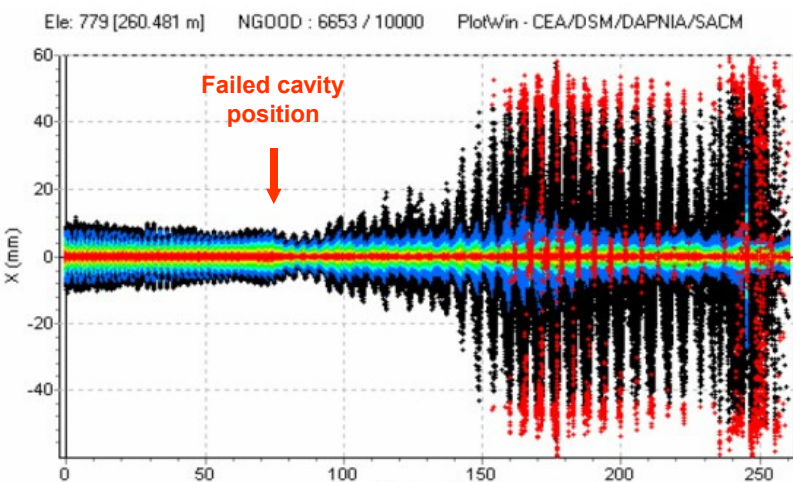
→ Two injectors

Serial redundancy: the requested functionality of a given element is ensured by means of **dynamic fault compensation** by non-failed elements, taking over the load of the failed one.

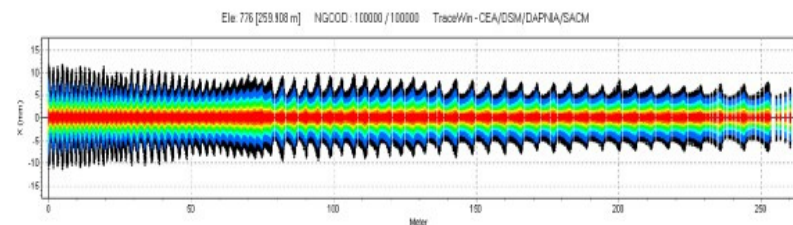
→ This implies that all elements must be operated well below their nominal performance



Dynamic Fault Compensation



After fault compensation



1. A failure is detected anywhere

→ Beam is stopped by the MPS in injector at t_0

→ Need for an efficient fault diagnostic system

2. The fault is localized in a sc cavity RF loop

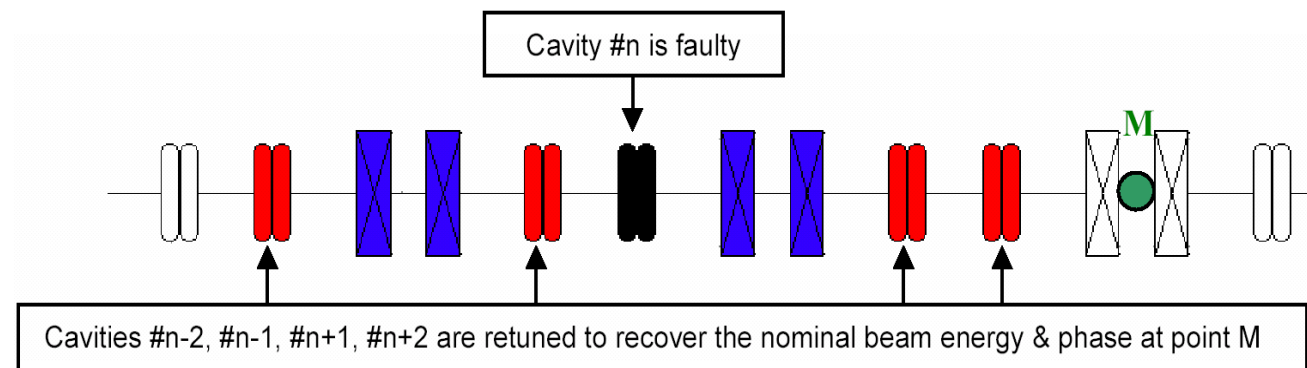
→ The failed cavity is detuned (to avoid beam loading effect)

3. Neighbouring cavities are retuned (amplitude and phase)

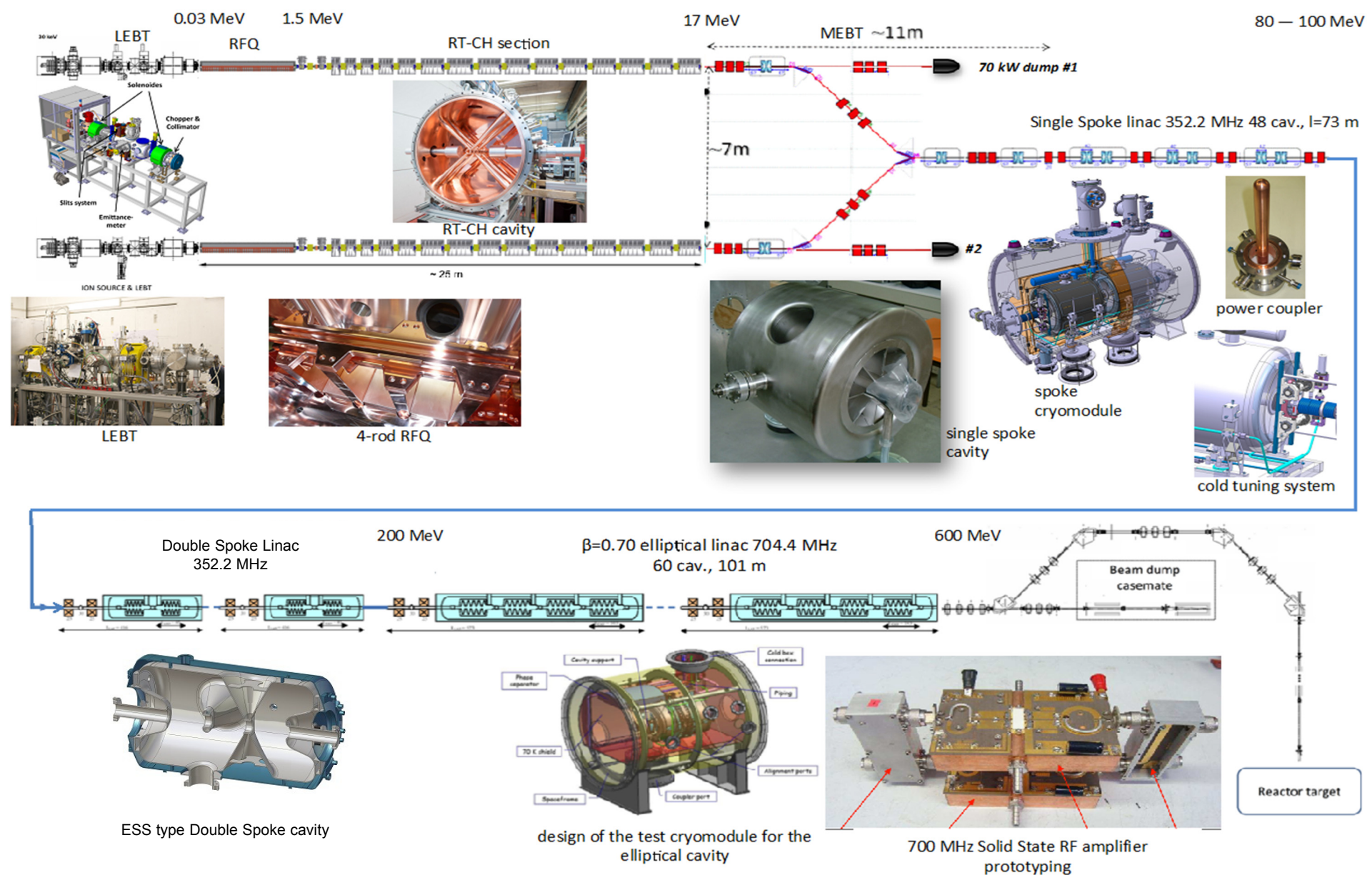
→ Need enough margin for amplifiers

→ Need enough margin for cavity gradients

4. Once steady state is reached, beam is resumed at $t_1 < t_0 + 3$ sec



Detailed Overview MYRRHA Linac



Decision to build in Mol/Belgium a new large research infrastructure MYRRHA in 2018

Staging of Project

Phase 1 (2019-2026)

Construction of 100 MeV Linac
and Proton Target Facility
Further R&D on 600 MeV Linac
and Reactor

Phase 2+3 (2027-2033)

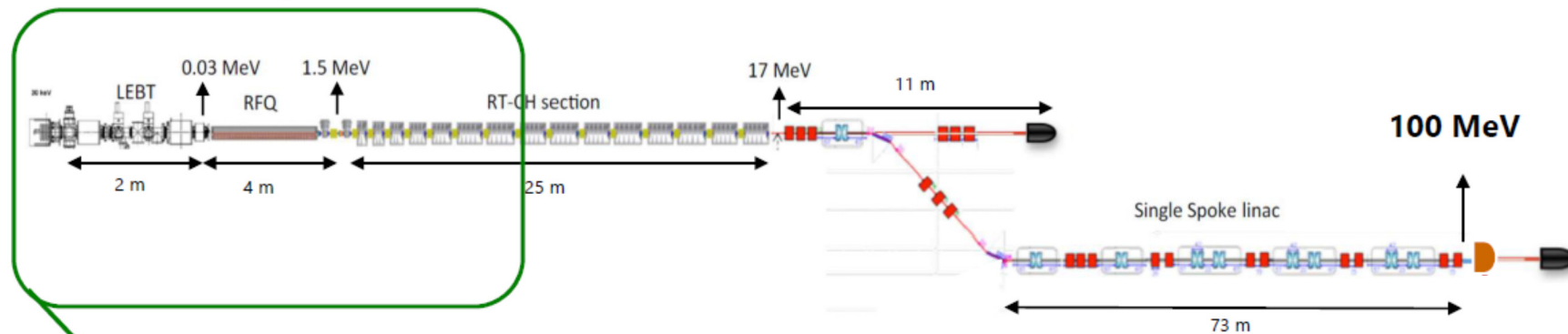
Construction of 600 MeV Linac
Construction of Reactor

The reasons for this approach are to construct, test and operate a representative section of the MYRRHA accelerator (MINERVA).

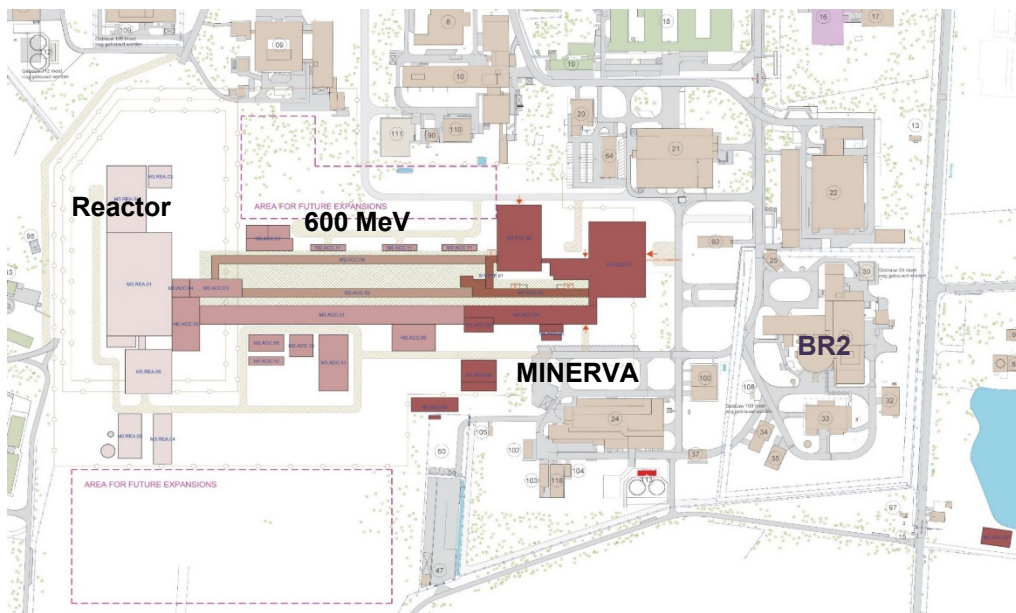
This is particularly important with respect to reliability of the MYRRHA Linac and to demonstrate the feasibility of fault compensation.

100 MeV Linac

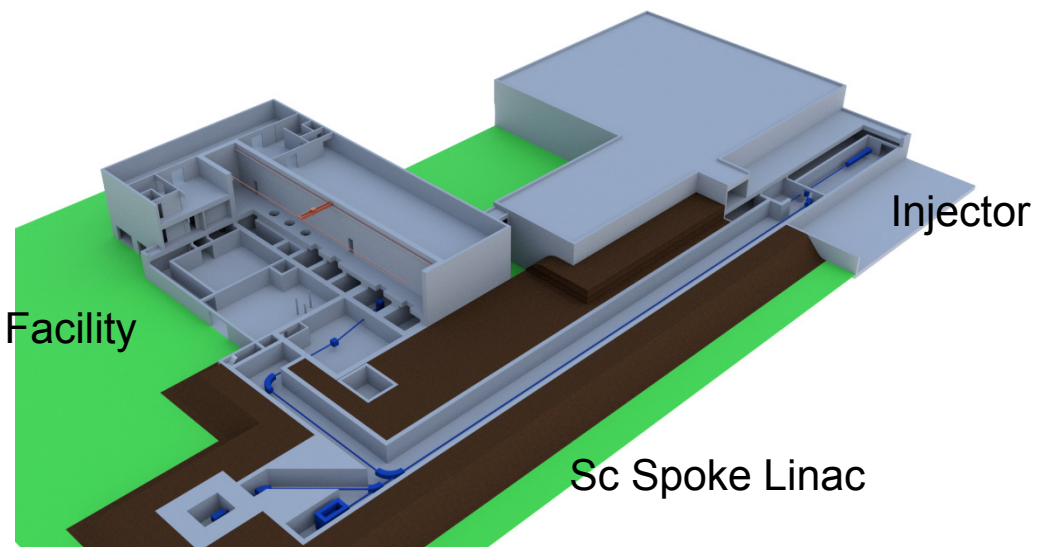
100 MeV proton linac



At SCK•CEN vault @CRC/LLN up to 5.9 MeV

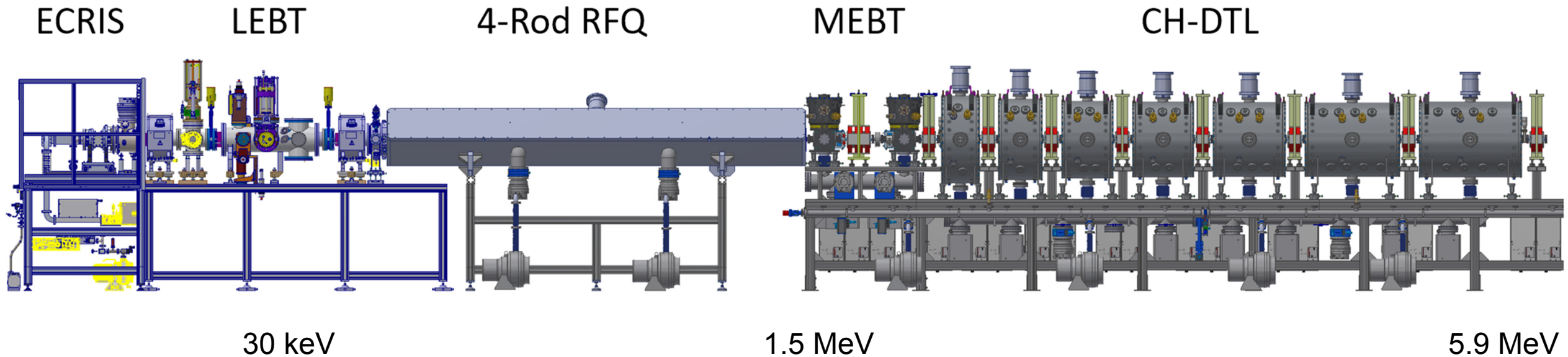


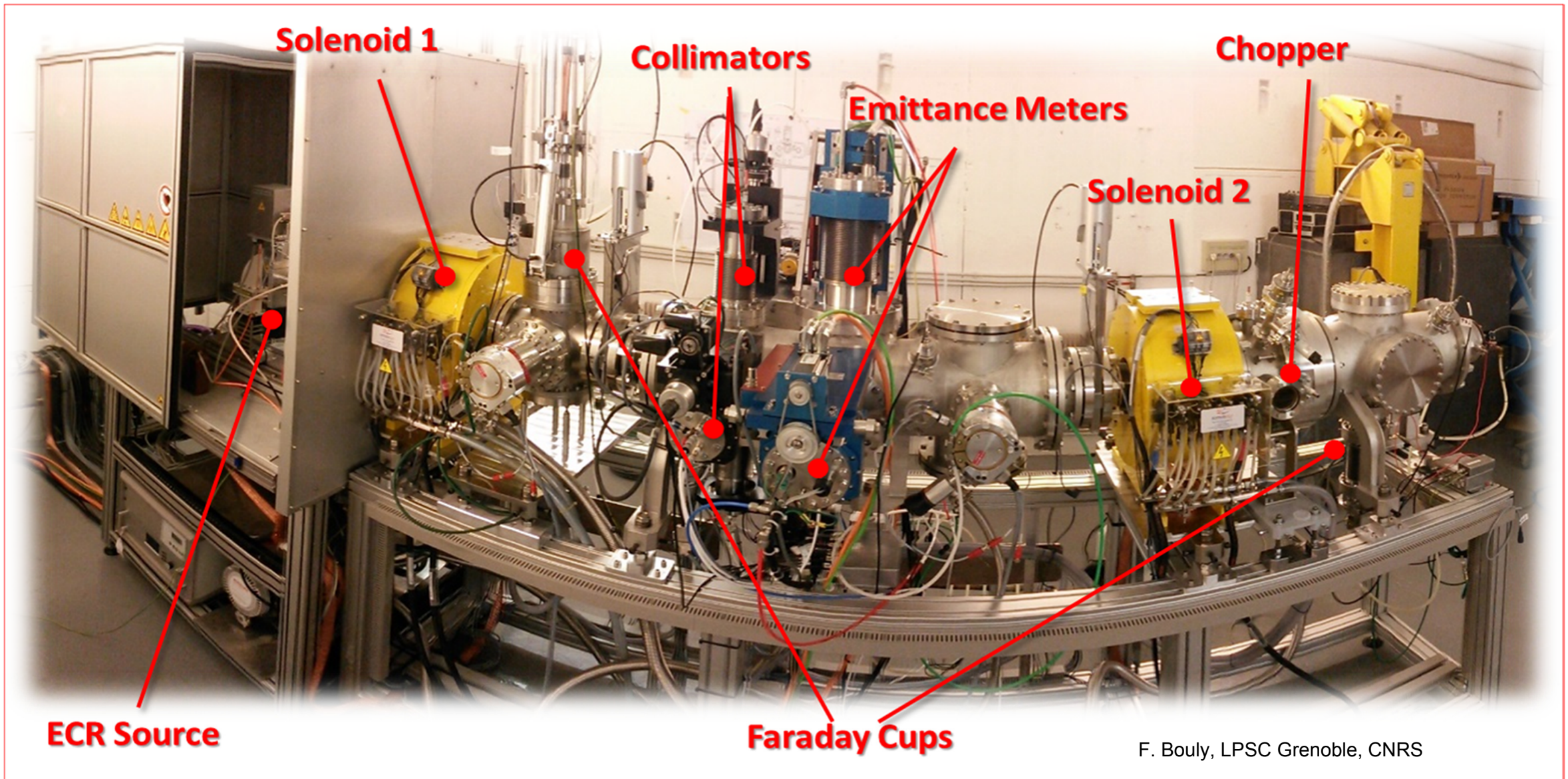
Target Station Facility



The construction of the first part of the MYRRHA injector up to 5.9 MeV has started

First installation at the cyclotron center in Louvain-la-Neuve (Belgium)





Maximum transmission with minimum emittance

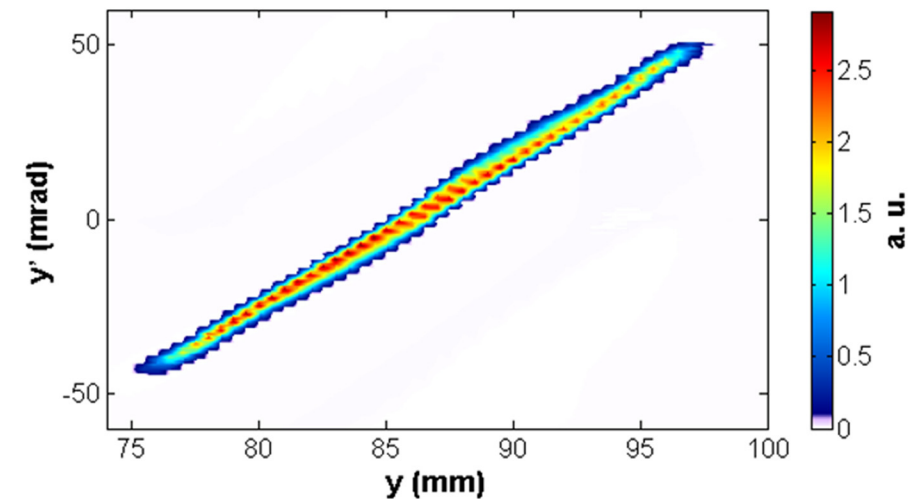
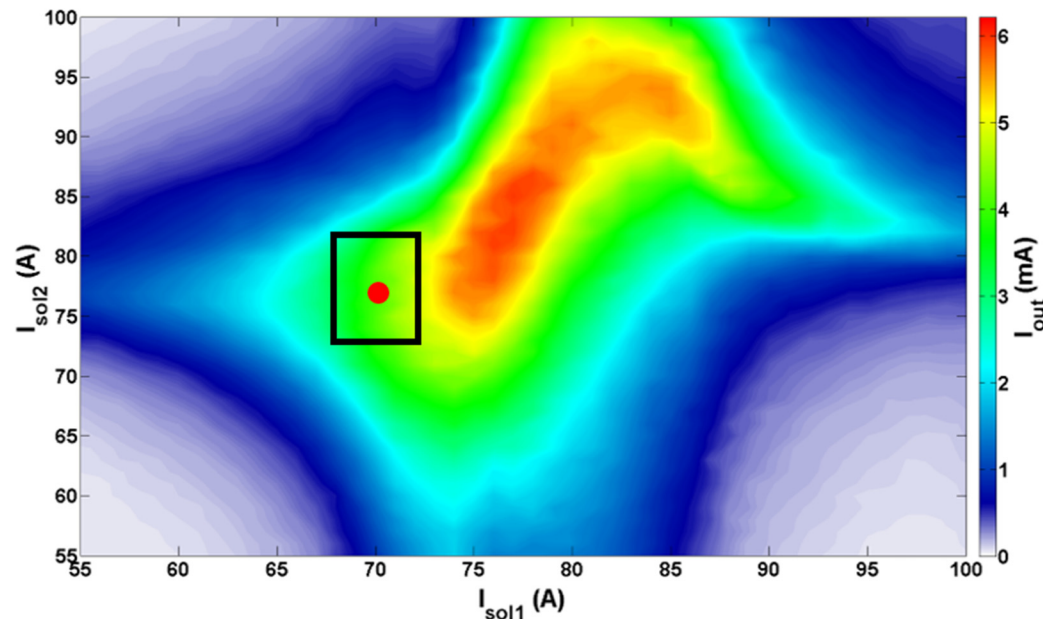
Optimization of beam parameter for RFQ injection

Systematic investigation of beam transport

Space charge experiments

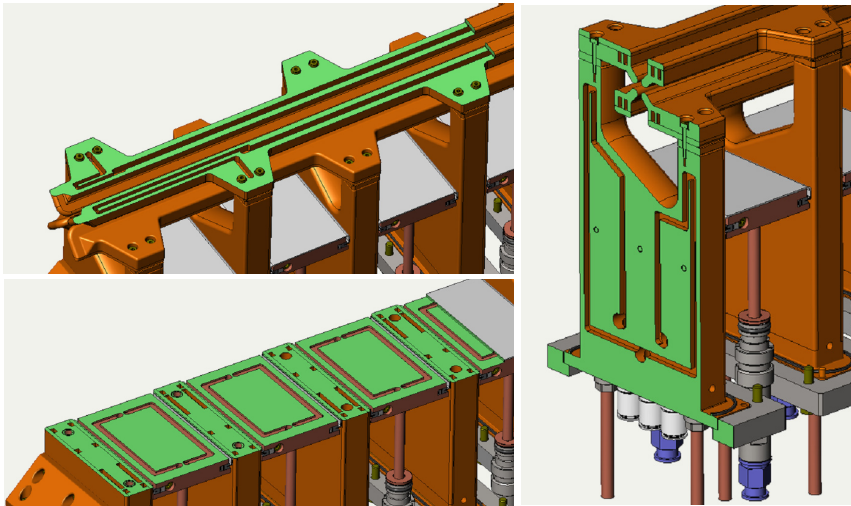
Front-End has been fully characterized

$\varepsilon_{\text{rms},N} < 0.2 \pi \text{ mm mrad}$ at RFQ entrance

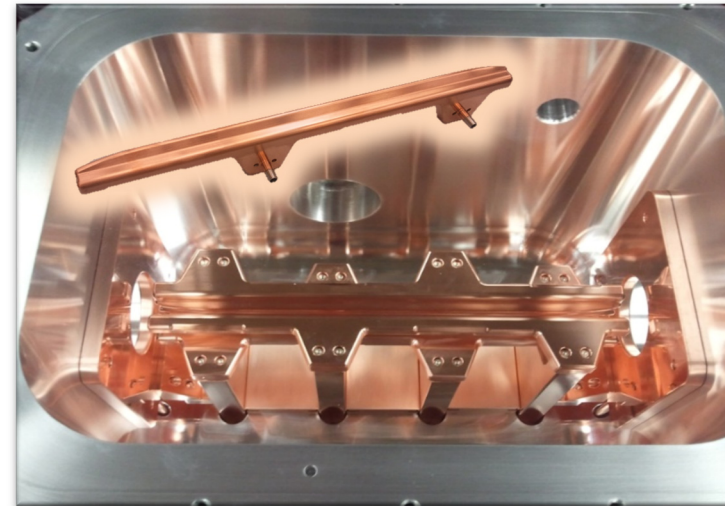


A 4-Rod RFQ has been chosen with conservative design

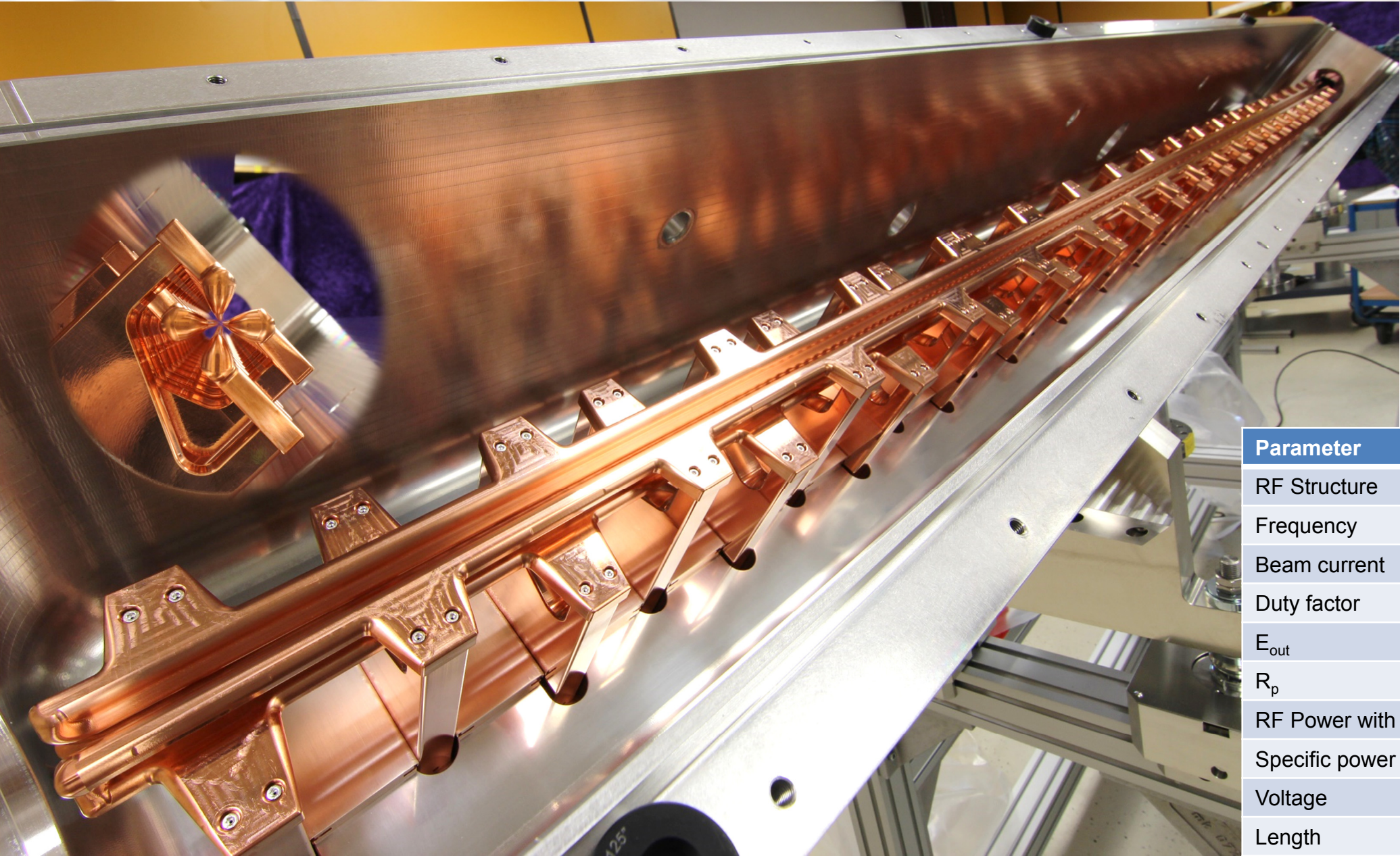
- Moderate voltage: 44 kV
- Moderate thermal load: 26 kW/m
- Well improved cooling
- Beam dynamics optimization with emphasis on longitudinal phase space



Optimized cooling channels

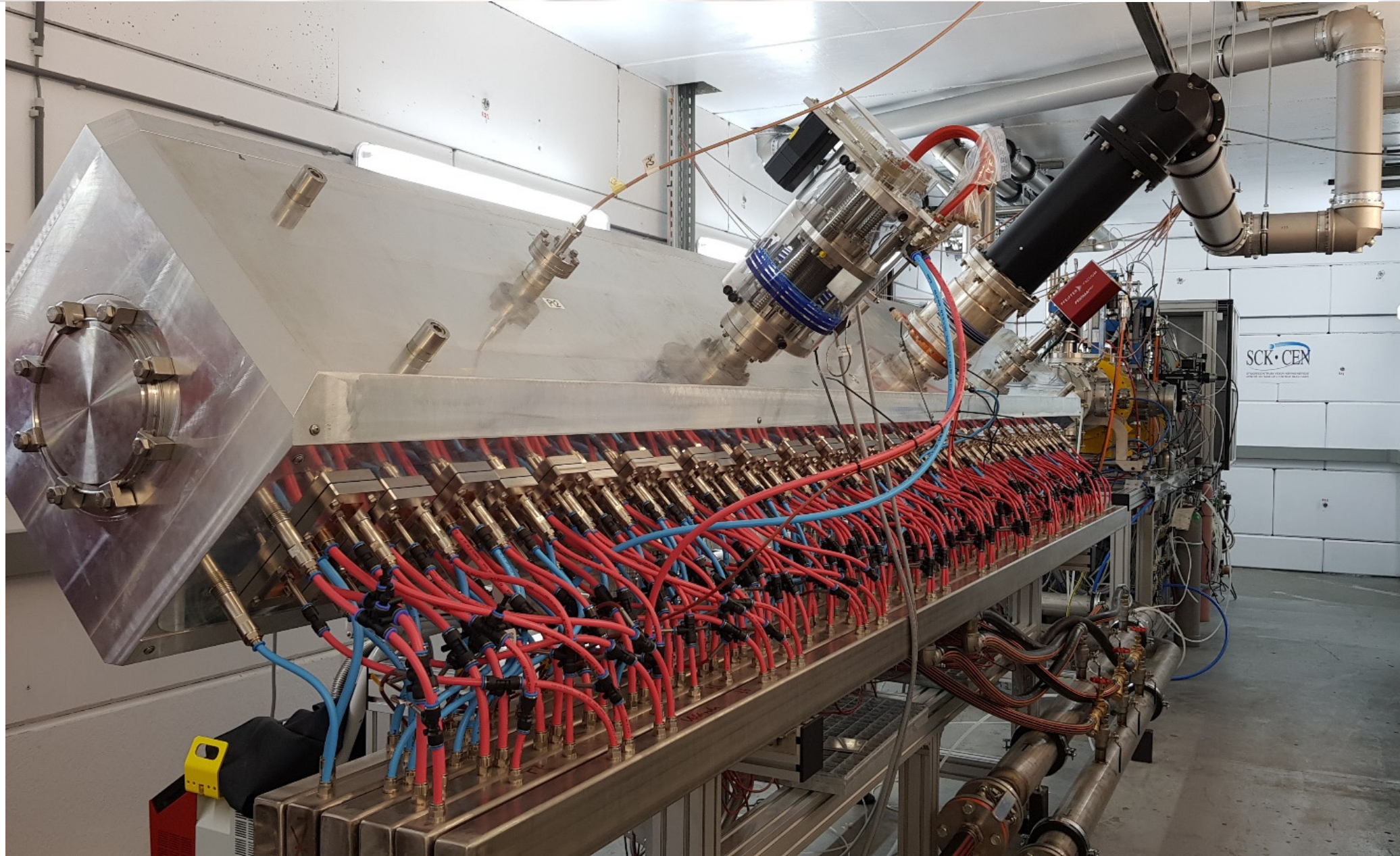


Short prototype has been tested up 120 kW/m cw



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 with beam	113	kW
Specific power loss	26.5	kW/m
Voltage	44	kV
Length	4	m

MYRRHA RFQ in
LLN prepared for
high power tests

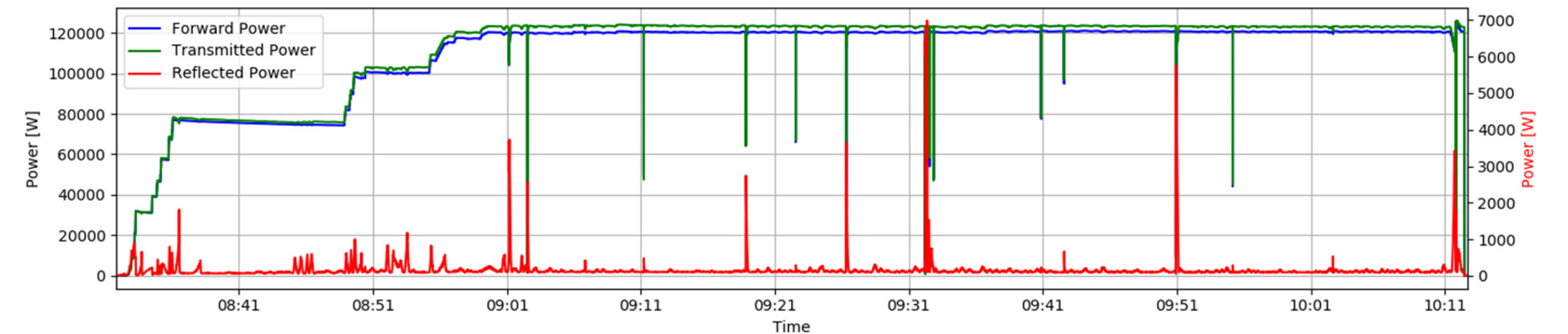
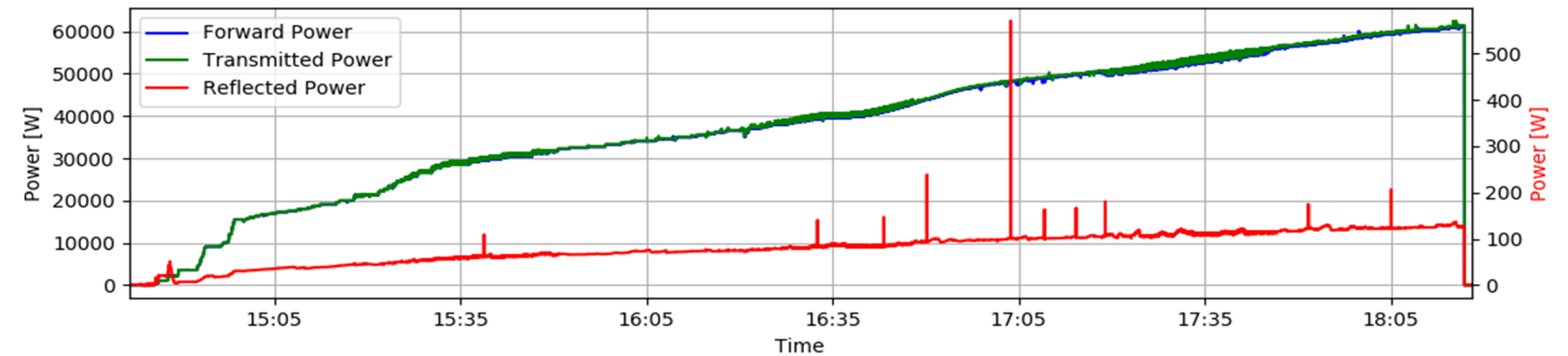
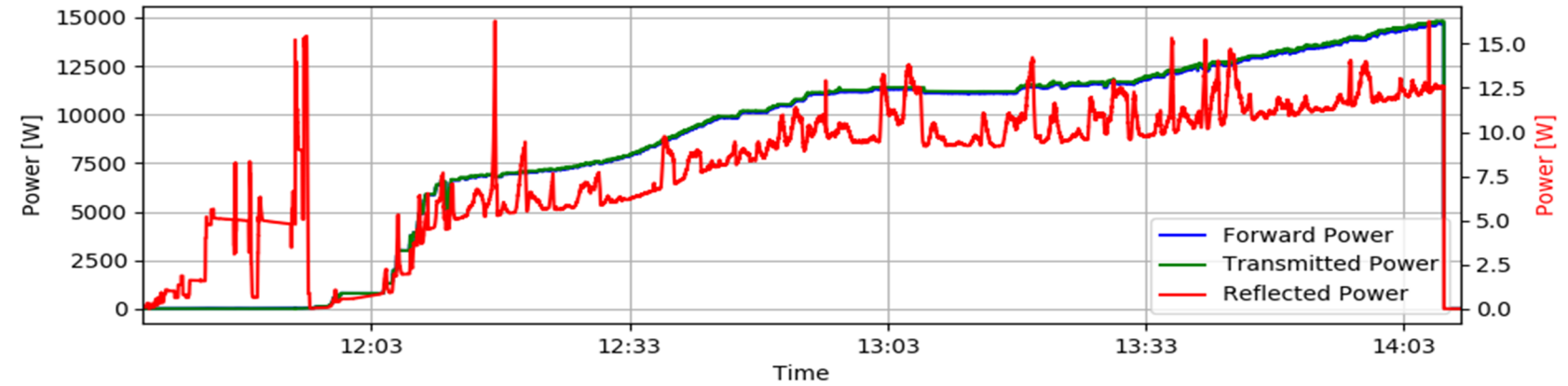


The RFQ requires about 108 kW RF power (losses)

Conditioned up to 145 kW cw

Conditioning time about 10 work days

First beam tests in 2020

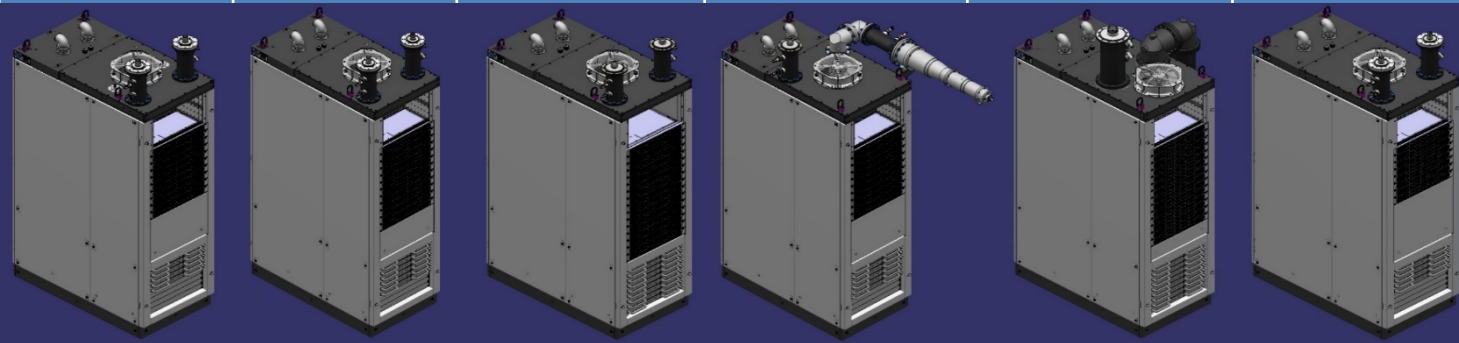


RF Power Amplifiers

- The RF system is very critical wrt to reliability
 - Solid state amplifiers can provide high reliability
 - SSA for the RFQ has been built and tested
 - $P=192$ kW cw
 - All amplifiers have the same architecture
- 6 kW RF pallets (6 transistors, MRF1K50N)
→ commercial power supplies (Astrodyne) in parallel

M. Abs, J. Brison, IBA

QWR1&2 (2 x 6 kW) CH1&2 (2 x 24 kW) 176 MHz	CH3&4 (2 x 36 kW) 176 MHz	CH5&7 (2 x 48 kW) 176 MHz	CH6 (60 kW) 176 MHz	Coupler test (80 kW) 352 MHz	Cryomodule test (2 x 20 kW) 352 MHz
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Design philosophy Injector DTL

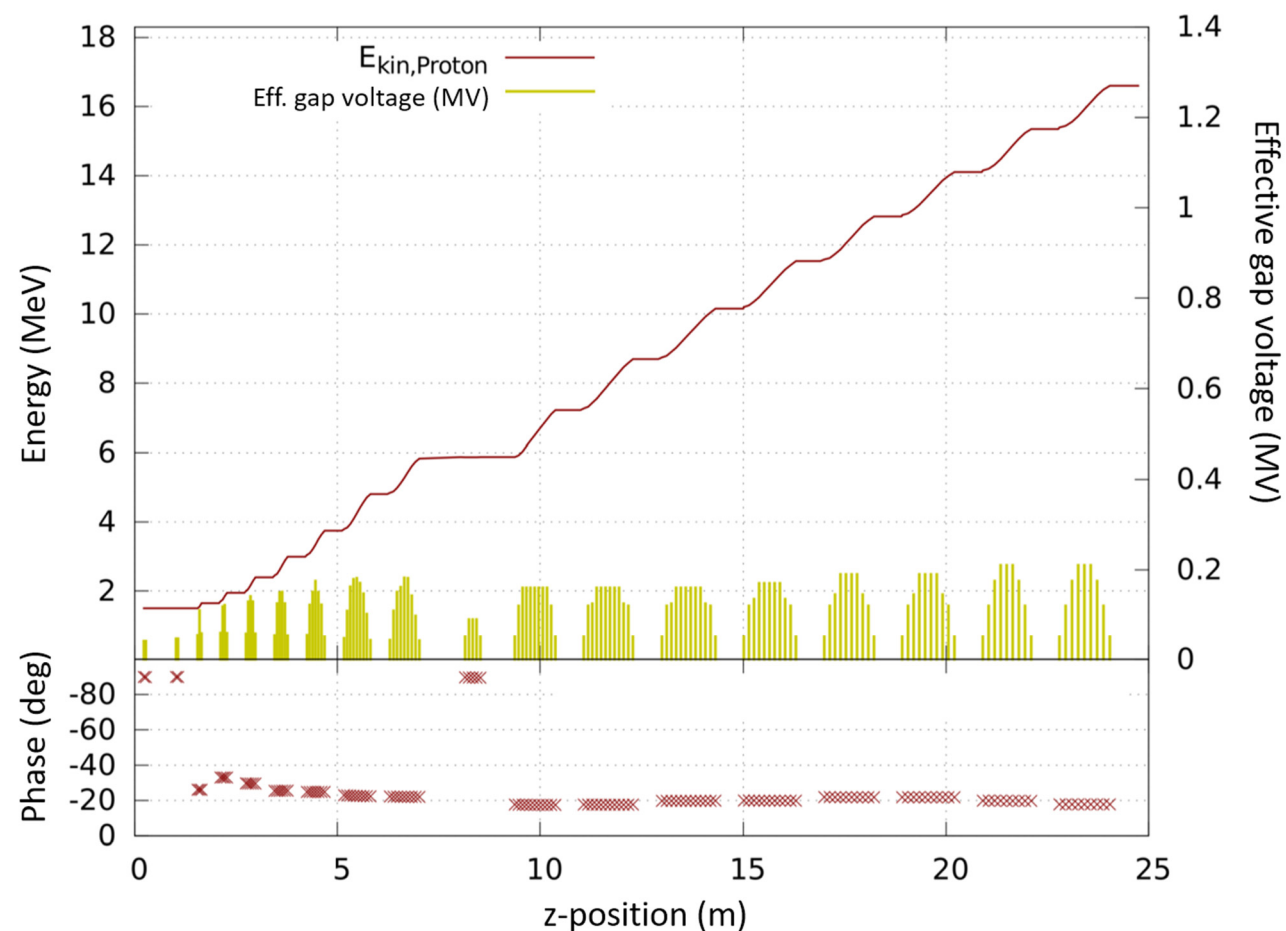
As conservative as necessary, as efficient as possible

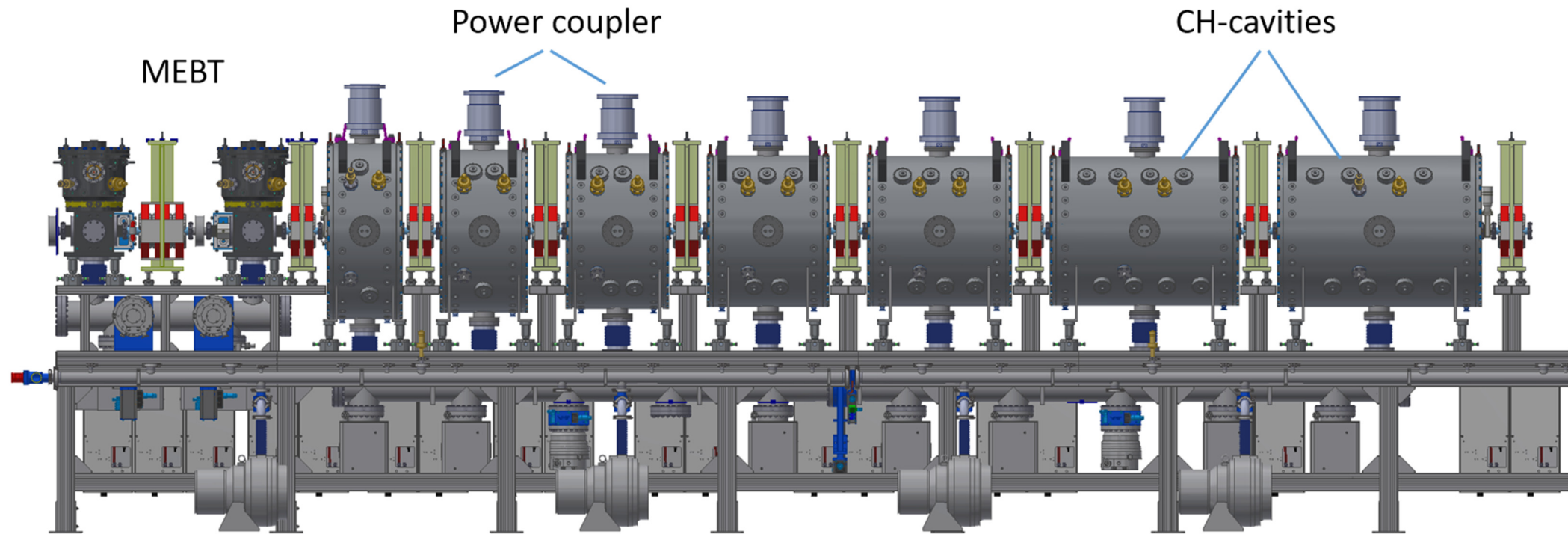
The injector DTL is based on rt CH-cavities

15 cavities are used (+ 1 CH-rebuncher)

Conservative beam dynamics (const. synch. phase)

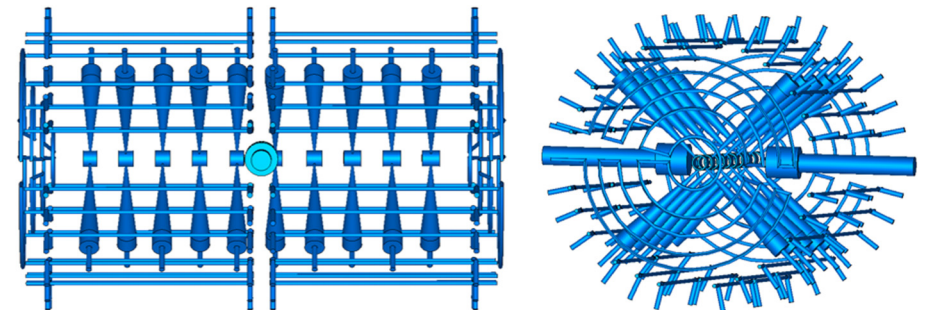
Quasi-periodic lattice (doublets between cavities)





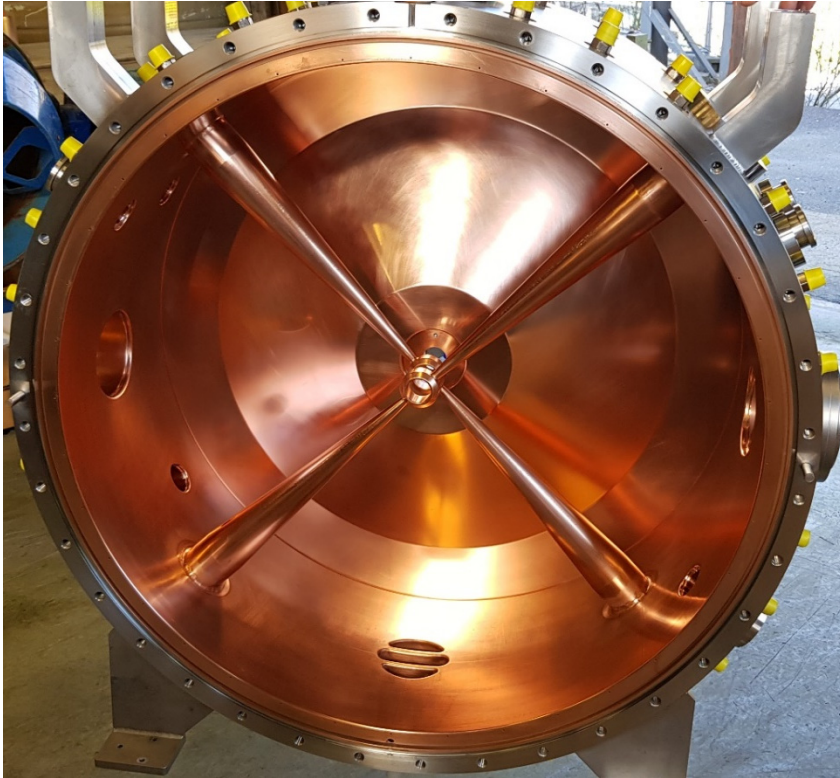
First CH-DTL section up to 5.9 MeV presently under construction

- MEBT components constructed and delivered
- CH 1+2: conditioned
- All quads delivered
- All Power couplers delivered

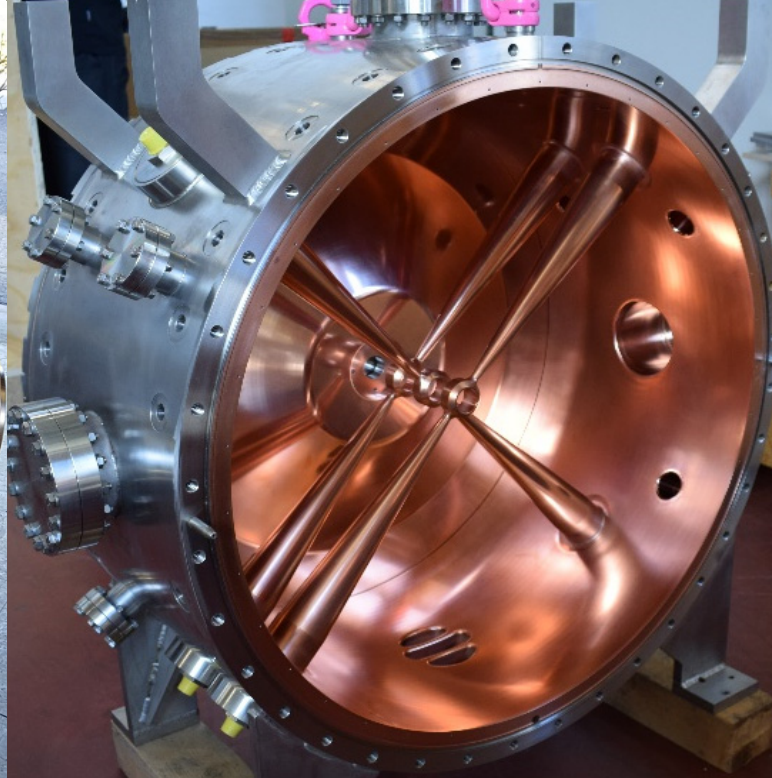


Cavity cooling

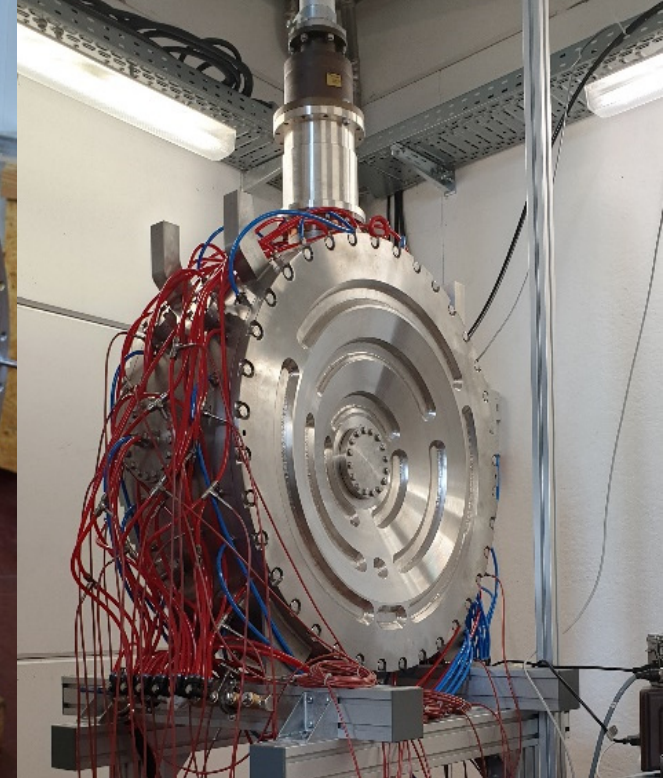
CH-1



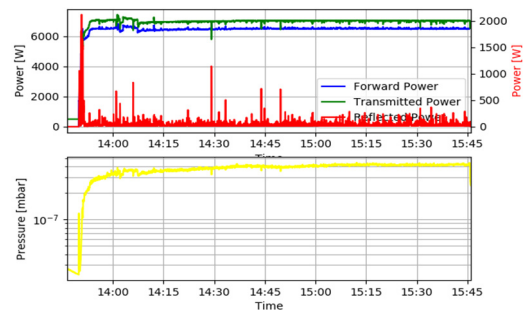
CH-2



High Power test stand at IAP



Commissioning CH-1



CH-2 has been commissioned last week without any problems

Call for tender for CH-3 to CH-7: This year

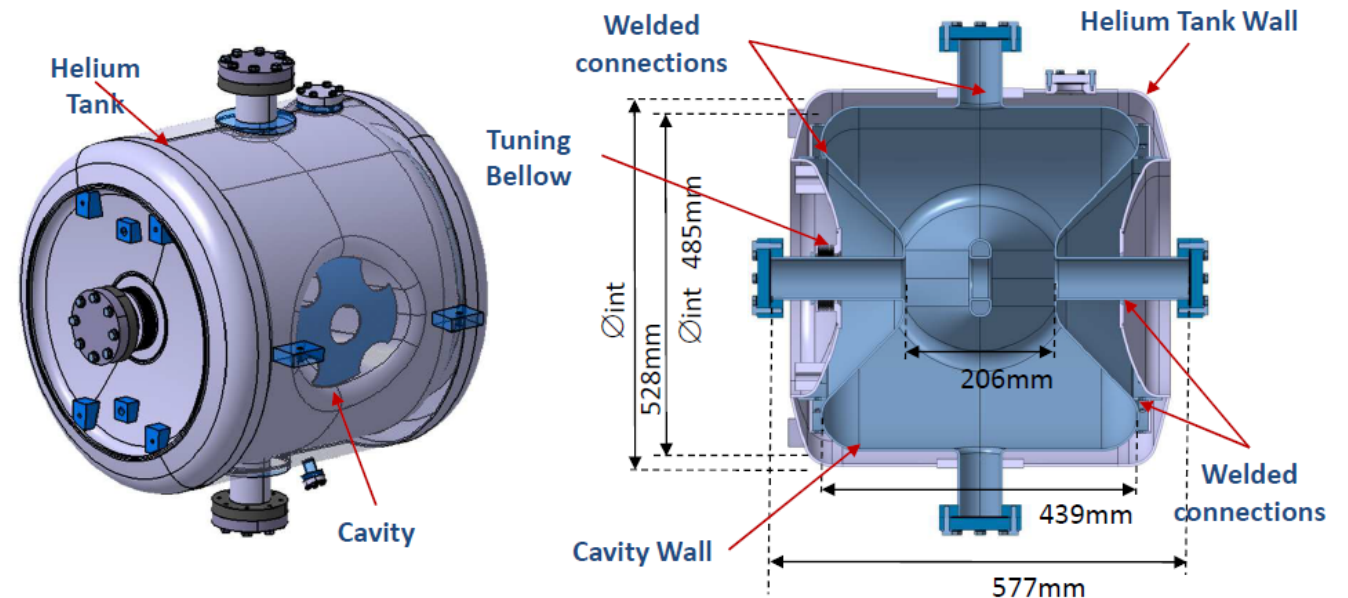
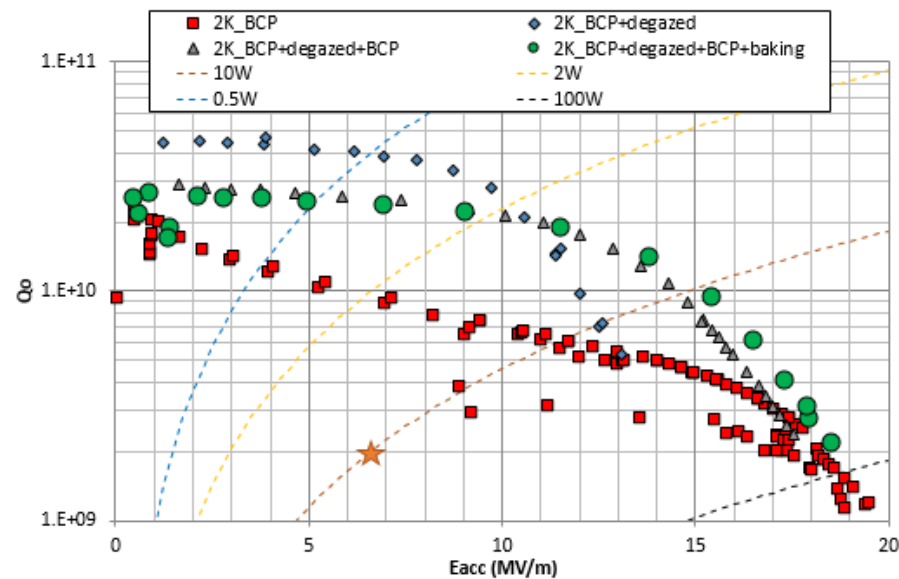
60 Spoke cavities cover the energy range between 17 and 100 MeV

$\beta=0.35$, $f=352.2$ MHz

Two prototypes have been developed and tested

Important issue was the **optimal surface treatment**:

An optimal surface treatment procedure has been defined: standard procedure + hydrogen degassing at 650°C during 10h without post chemical etching



Beam Dynamics is one of the **most important issues** for the **MYRRHA Linac**

Beam loss of a 600 MeV Linac with an average beam power of 2.4 MW should be as low as possible to prevent possible damage to components and to minimize activation

Excessive beam loss can result in a shut down and lower availability of the whole facility

Minimum emittance growth, maximum longitudinal acceptance

Several tools have been developed: Virtual accelerator, automatic retuning procedures after cavity failure compensation

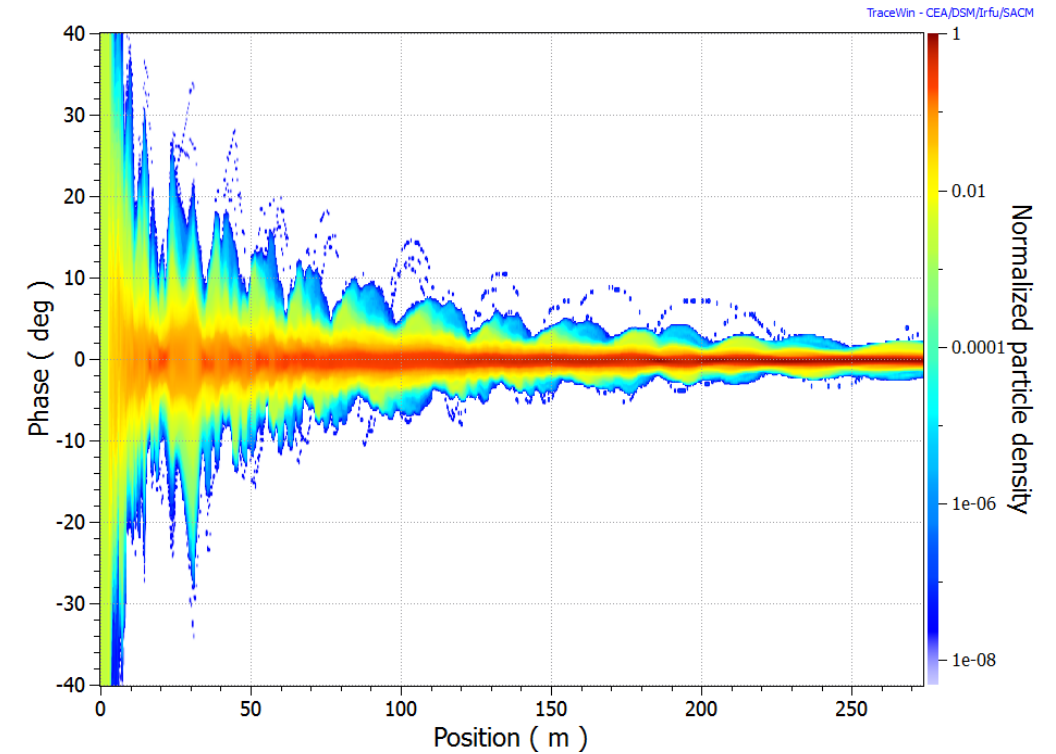
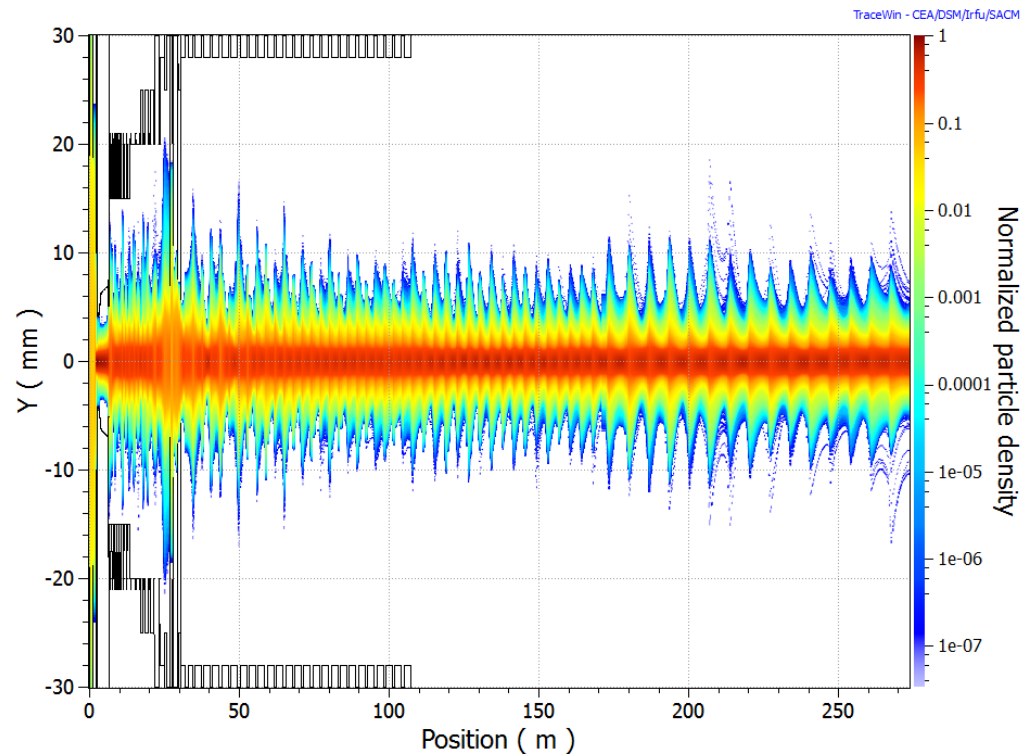
Done:

- Sensitivity analysis to check the robustness of beam dynamics regarding input beam mismatch
- Errors study
- Error study with cavity failures and compensation

End-to-End Simulations without Errors

Simulation with 100 million particles

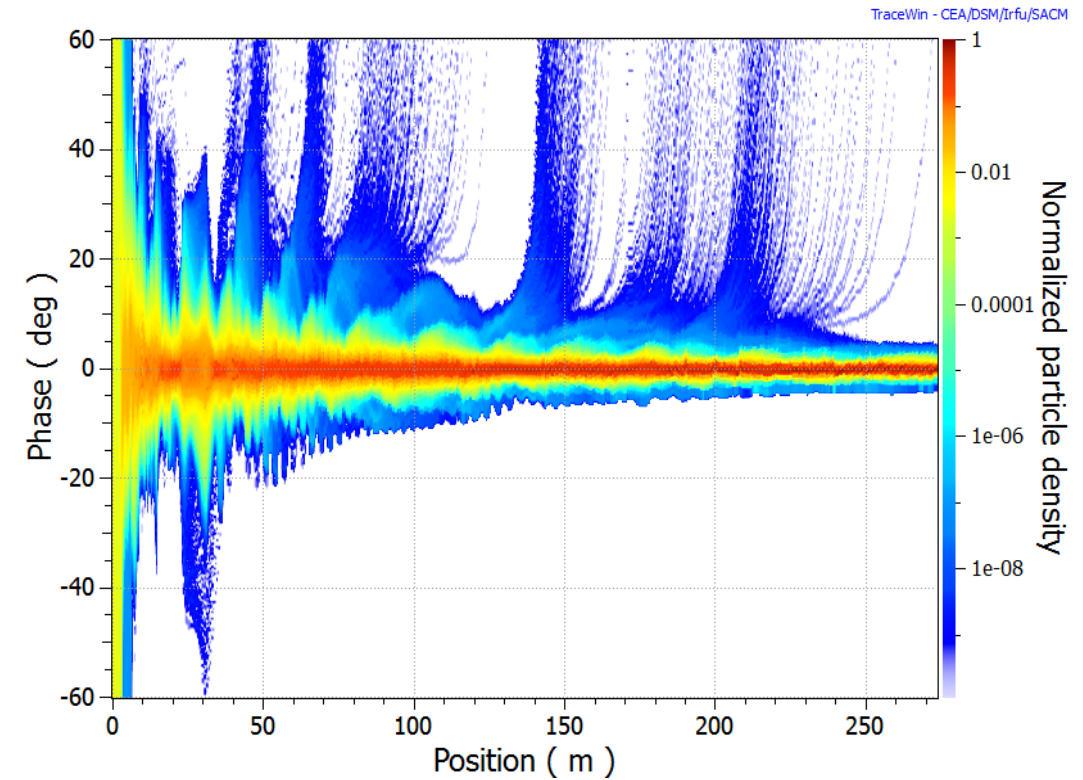
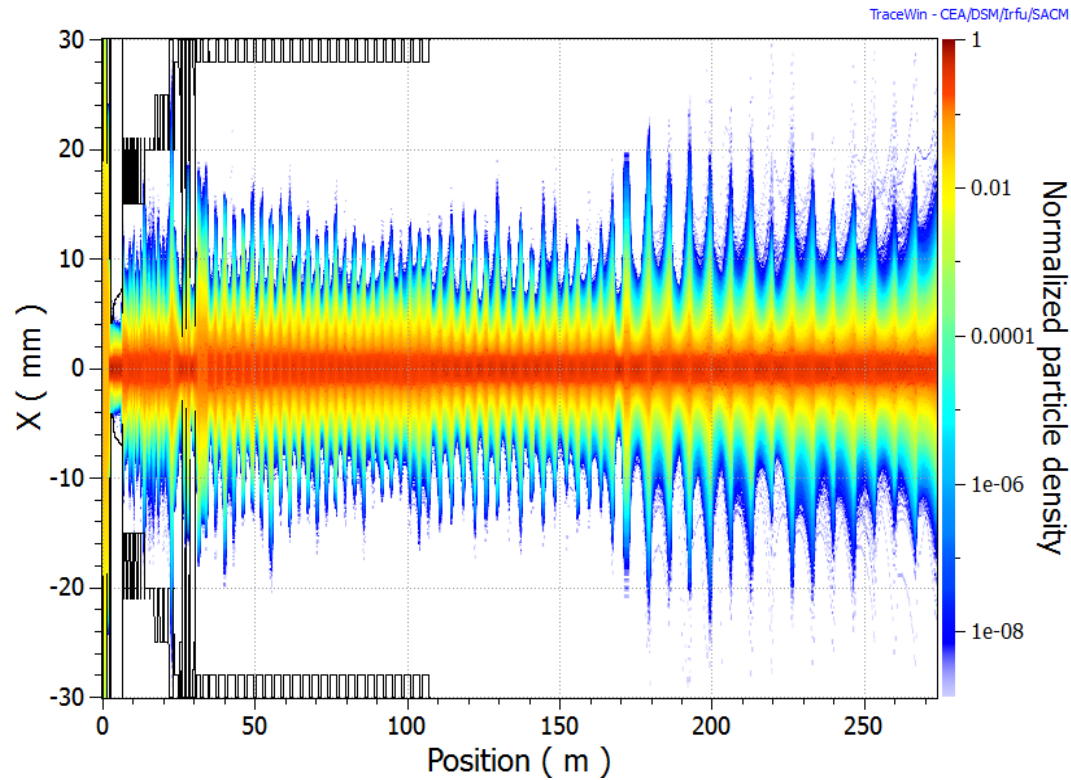
Realistic 3D field maps incl. the RFQ have been used



End-to-End Simulations **with** Errors

1000 Linacs with $3 \cdot 10^6$ particles each
Cumulative plot for all Linacs with 3 billion particles

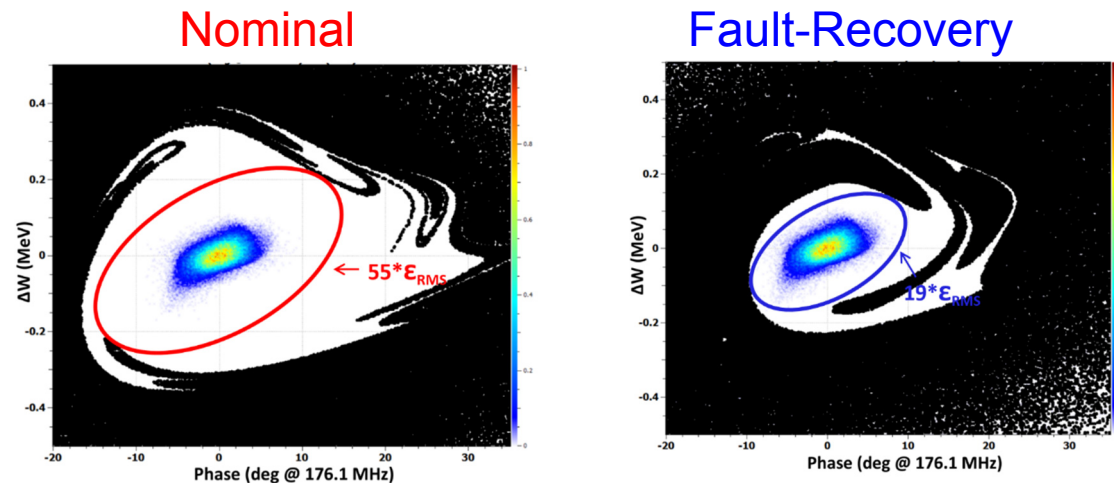
90% of Linacs do not show losses
99% have maximum losses of 0.2 W/m
Worst case 0.85 W/m locally



Cavity recovery issues:

Problem: Longitudinal acceptance is shrinking

Multi cavity failure: 1 Spoke-cavity, 1 cryomodule in section 2 and 1 elliptical cavity in section 3
Each cavity is compensated by 4 neighbouring cavities

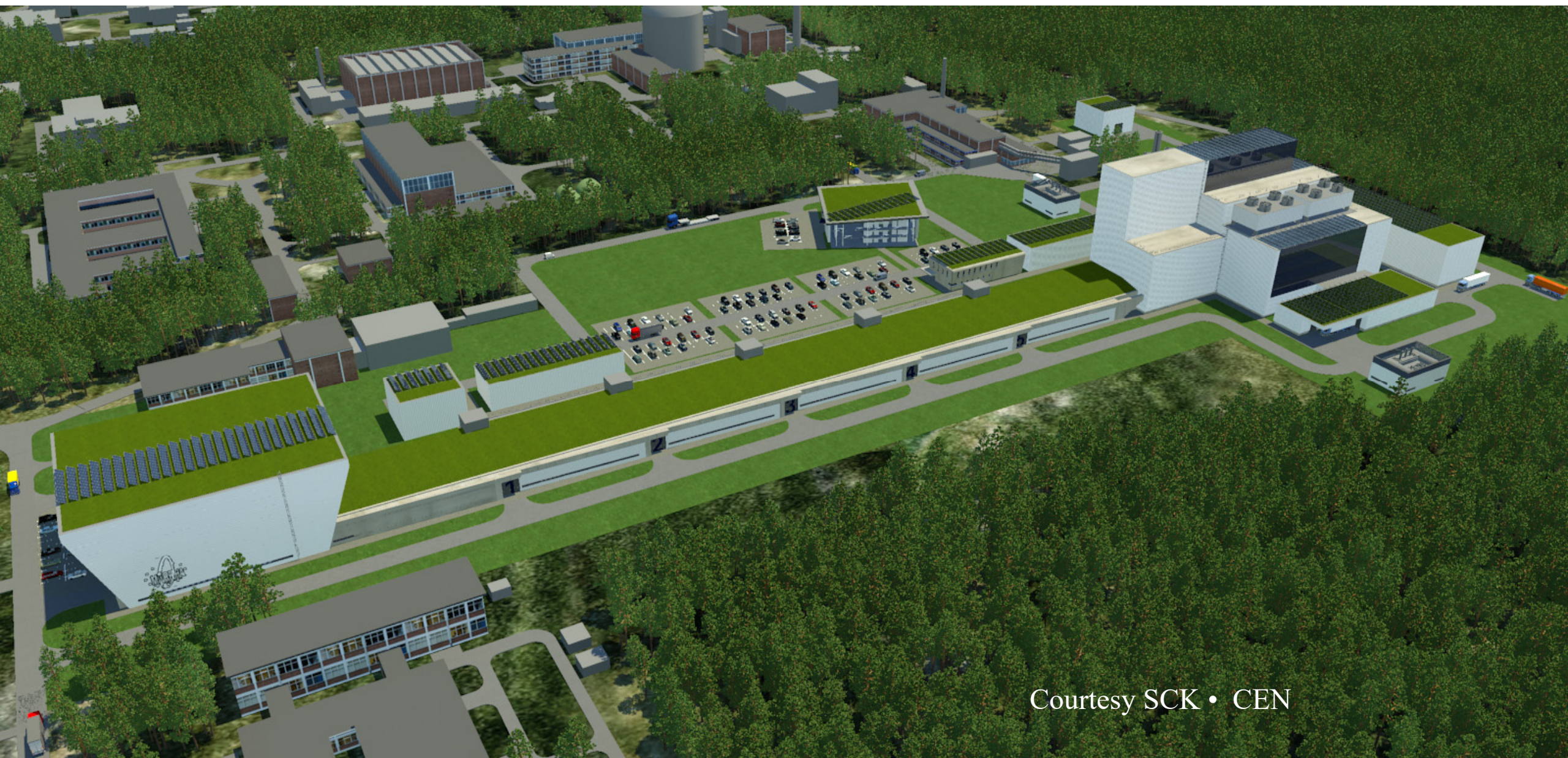


D. Uriot, CEA Saclay

Double-Spoke cavities @ 352 MHz instead of 5-cell elliptical at 704 MHz
→ Increase of longitudinal acceptance

Less aggressive compensation scheme, more cavities for compensation

A view into the future



Courtesy SCK • CEN

- The MYRRHA Project couples a 2.4 MW Proton-Linac to a 100 MW Reactor
- Decision to build the first 100 MeV section with target station in 2018
- Reliability of the Accelerator is the major issue to ensure the availability of the whole facility
 - Conservative design and redundancy, dynamic fault compensation
- Front-End (Source+LEBT) operational
- RFQ has been conditioned up to 145 kW cw
- CH-DTL under construction, CH1+2 are tested with high power
- Spoke prototypes are performing very well
- 100 MeV Linac operational 2026
- Full MYRRHA Project operational 2034

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